NORTHWESTERN UNIVERSITY

Fermilab

Dark Matter Search Results from the PICO-60 C_3F_8 Bubble Chamber

Dan Baxter

April 14, 2017

PICO

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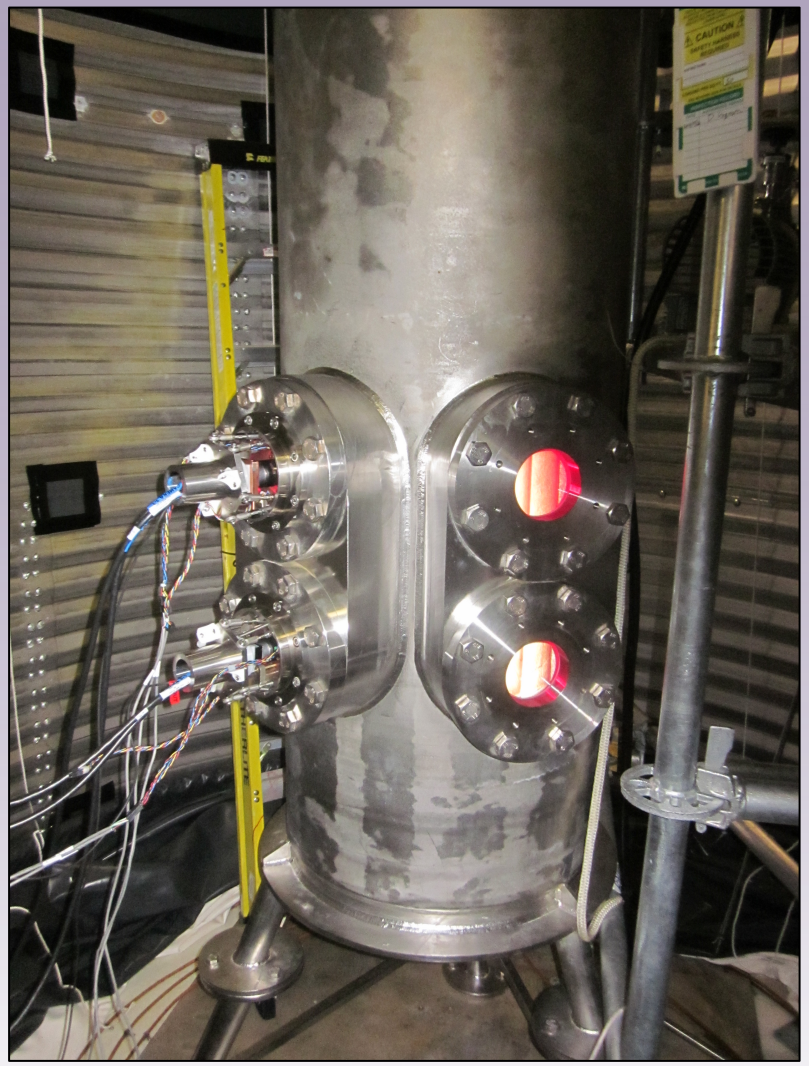
PICO

Overview

1. Motivation
2. Bubble Chamber Physics
3. Backgrounds to Dark Matter
4. New Results from PICO
5. PICO Future Plans



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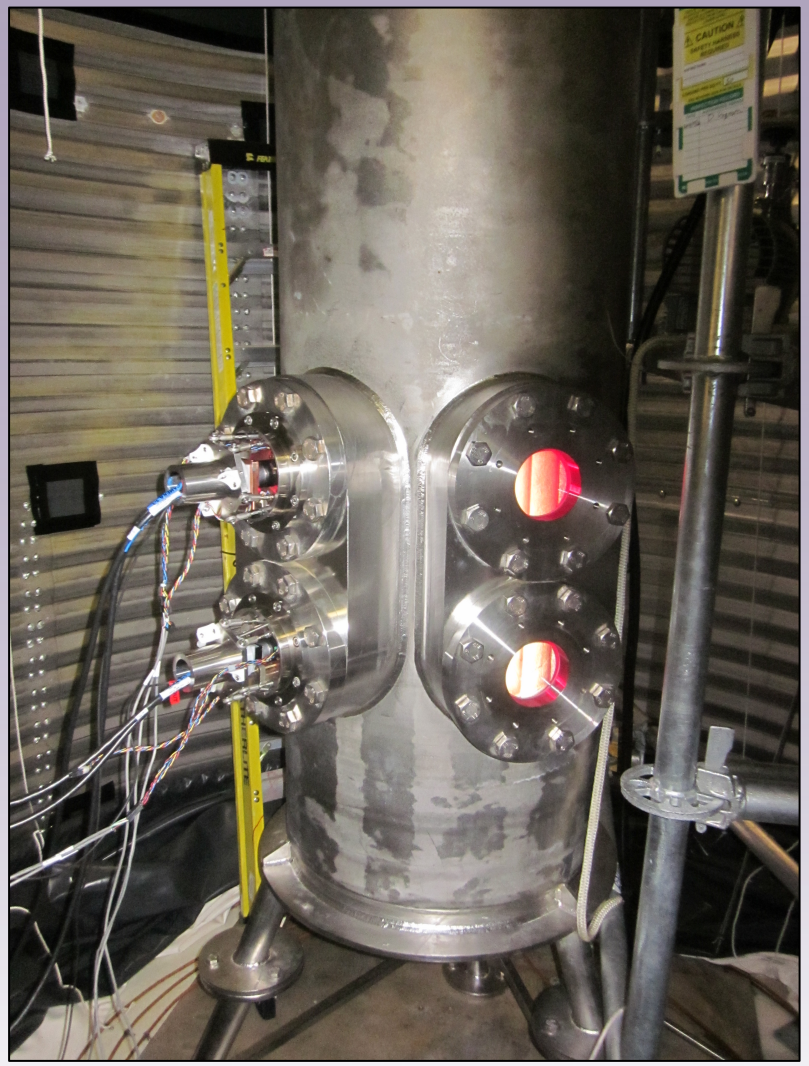
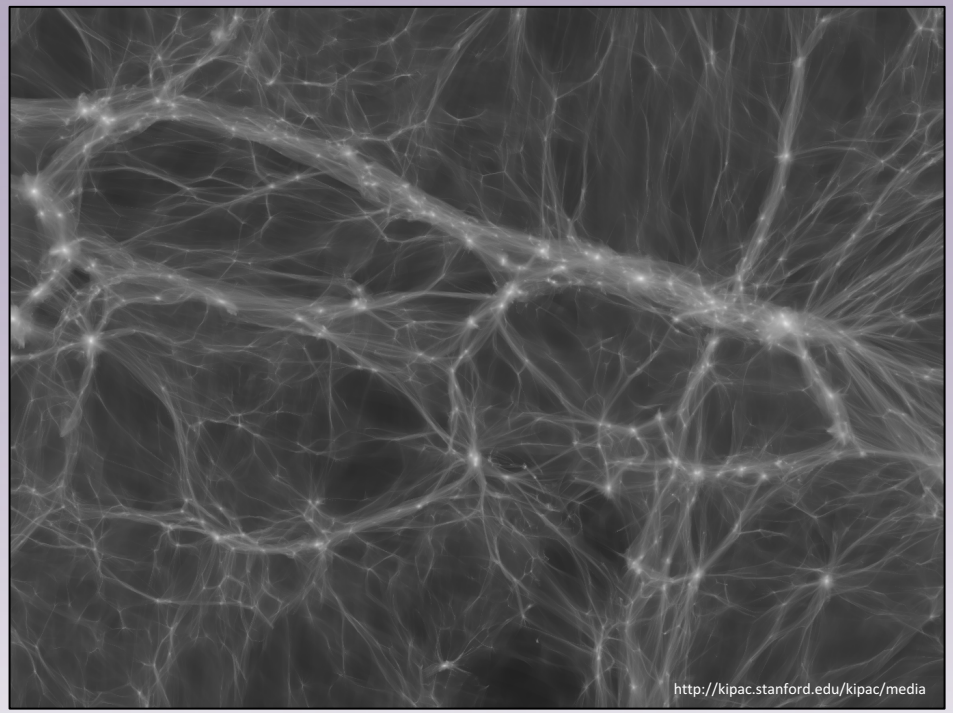


What is Dark Matter?

Dark matter is the name given to the unresolved problem of missing, non-baryonic mass in the universe.

Evidence:

- Galaxy Rotation
- CMB
- Lensing
- Bullet Cluster
- …and many more



Interactions:

- Gravity: YES (*matter*)
- EM: NO (*dark*)
- Weak-scale: maybe?
  - Weakly Interacting Massive Particles (WIMPs)

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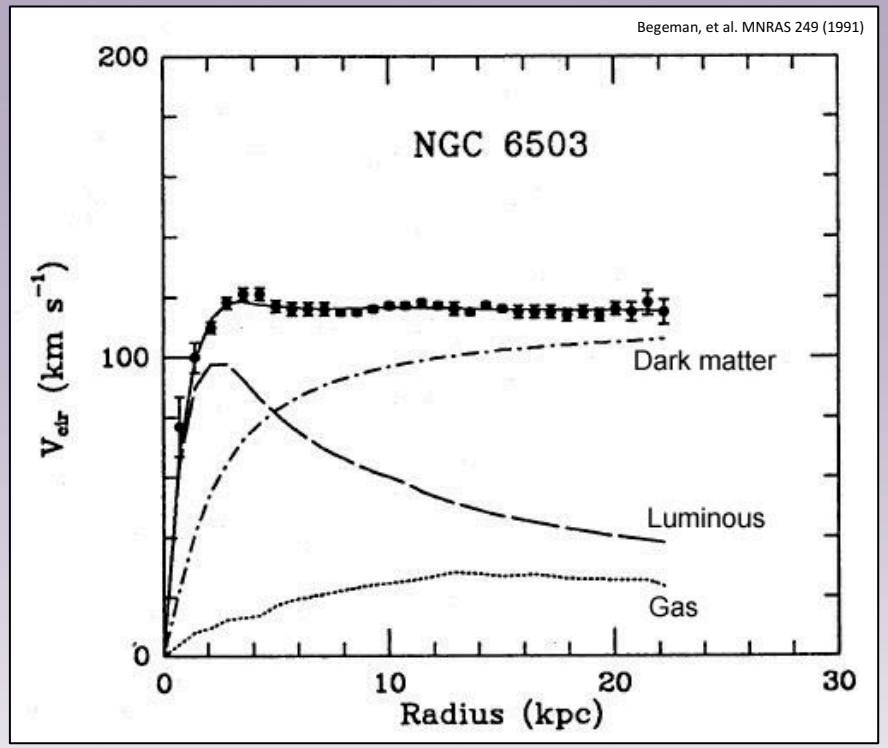

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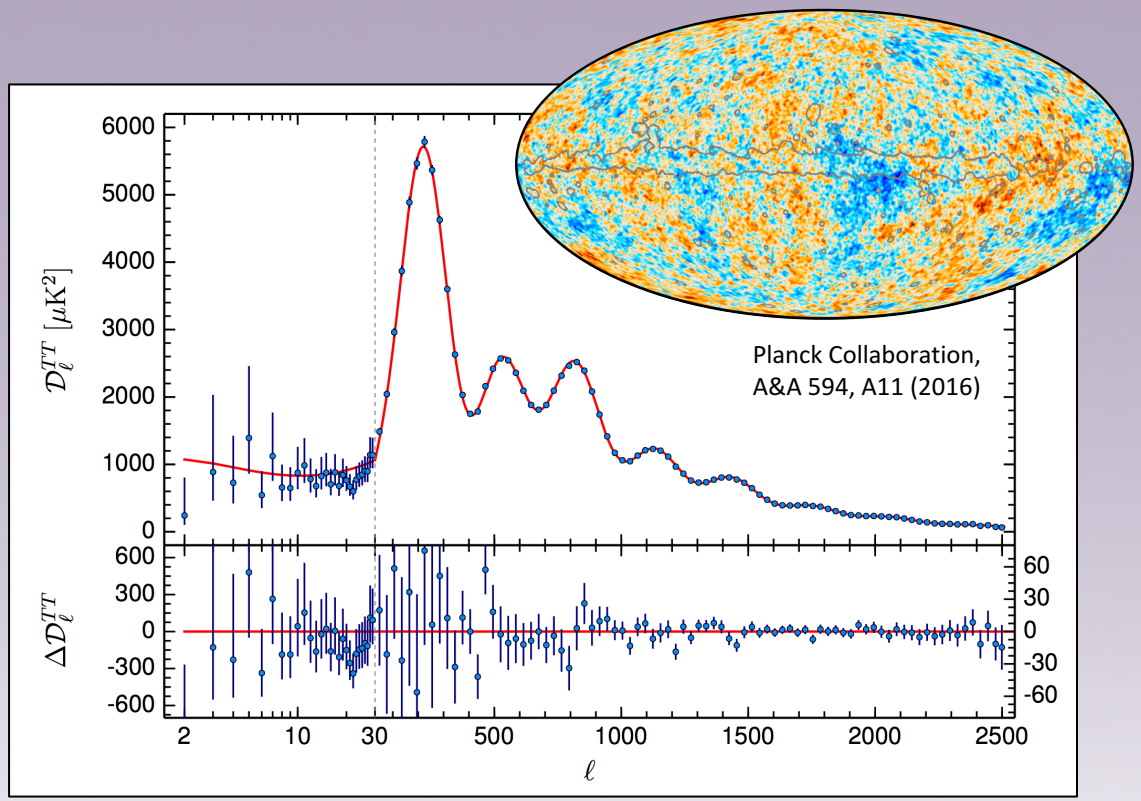

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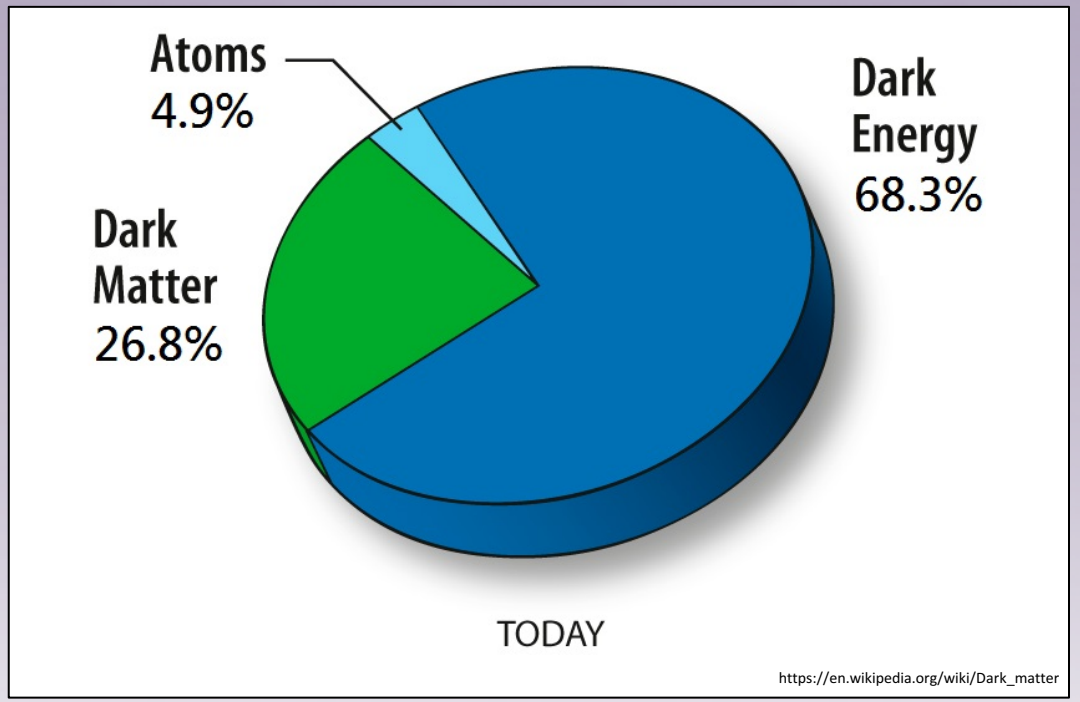

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- **Gravity: YES (*matter*)**
- **EM: NO (*dark*)**
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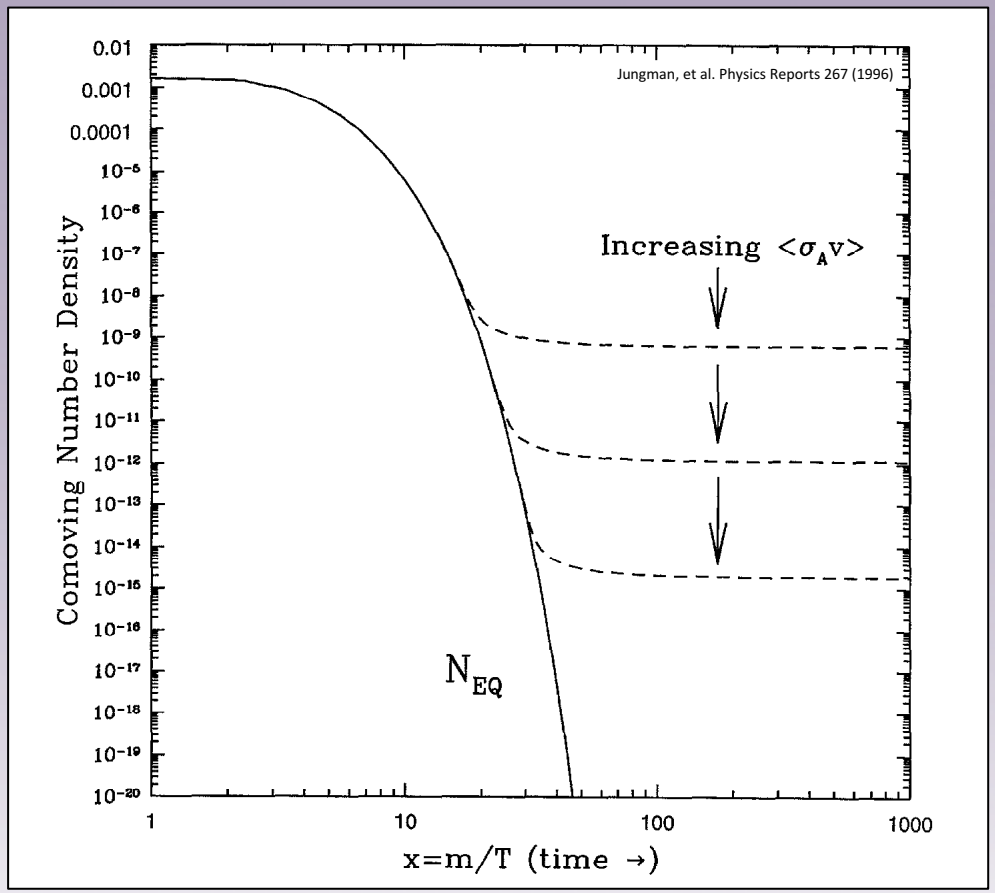
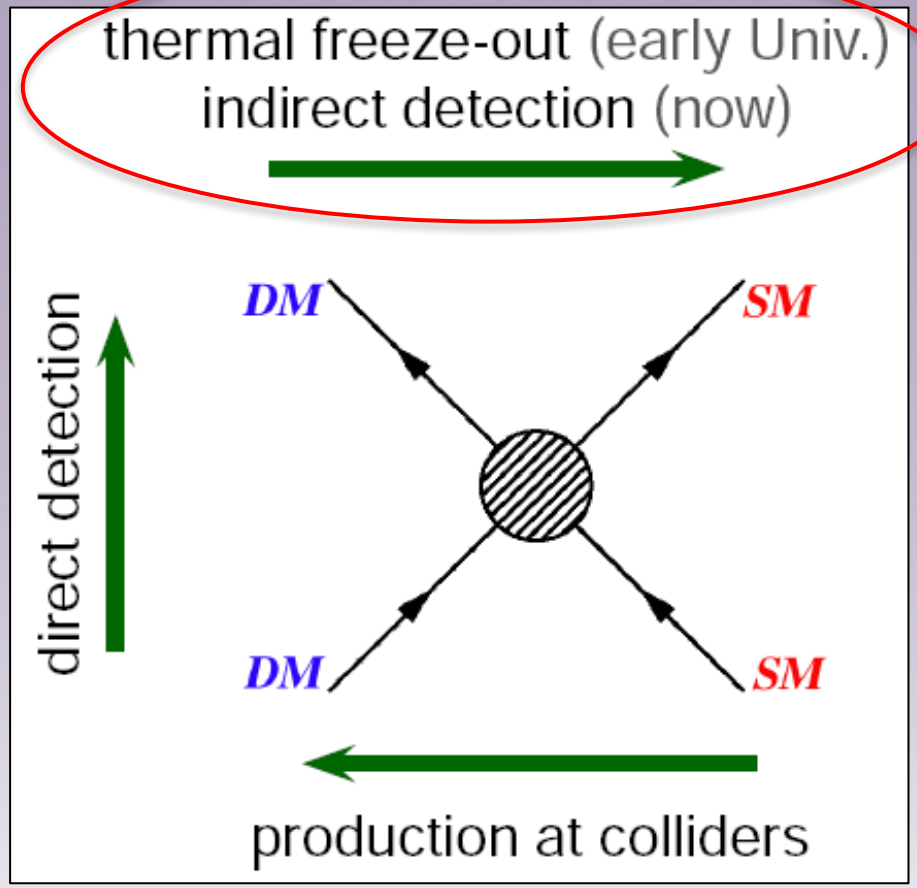
  - **Weakly Interacting Massive Particles (WIMPs)**

Weakly Interacting Massive Particles

- Natural production mechanism in early universe
- Freeze-out with annihilation cross section of order weak-scale gives roughly the relic density
- Mass of order 1-1000 GeV
- Lightest SUSY particle would qualify as a WIMP

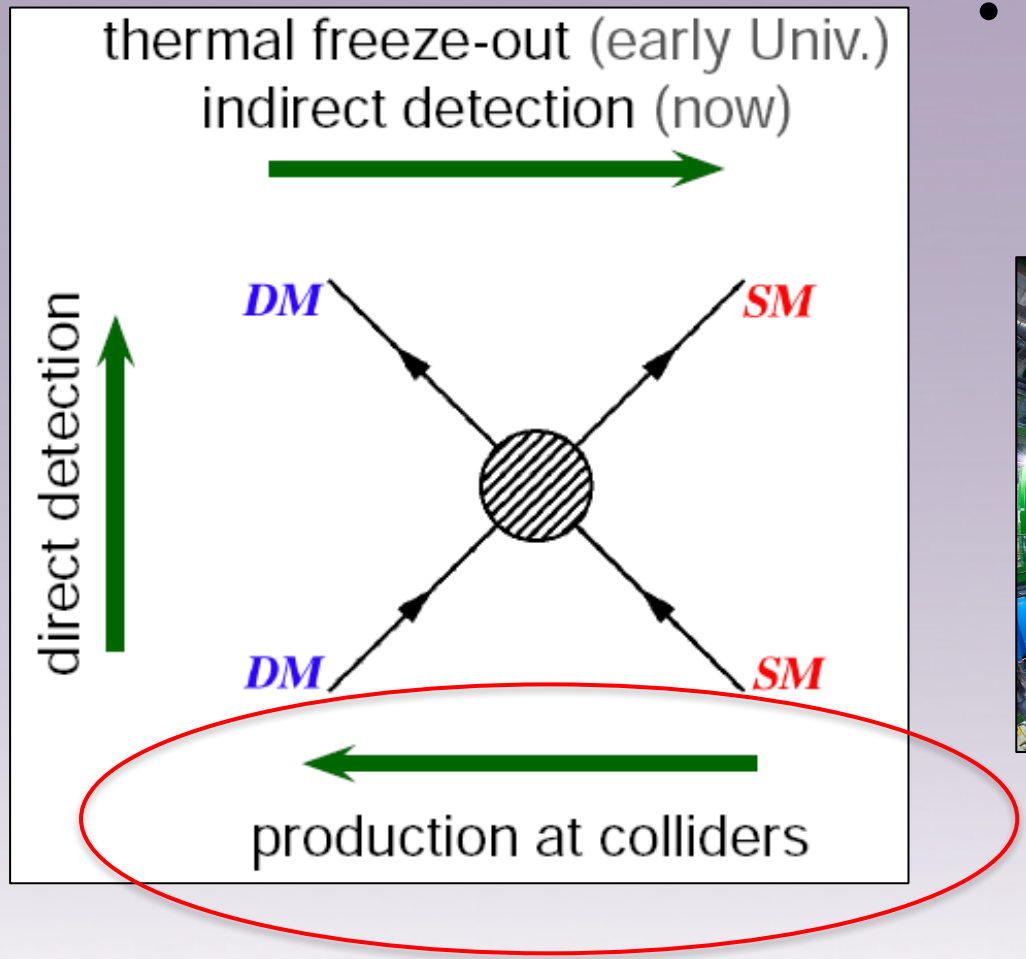


Detecting Dark Matter

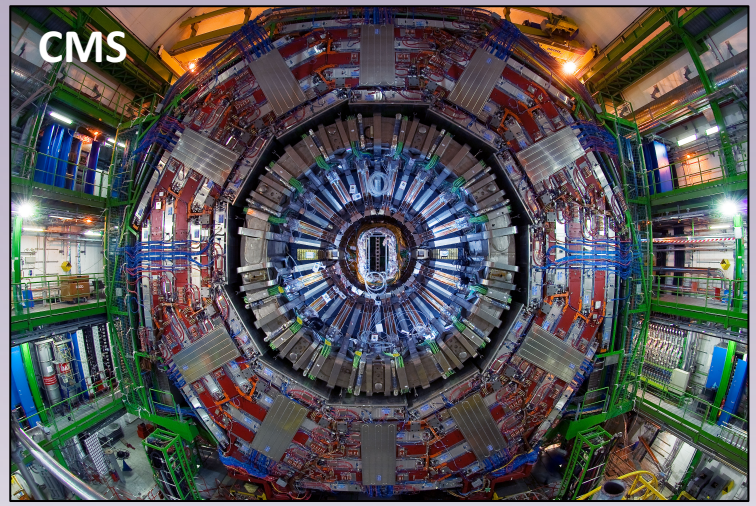


- Look for annihilation signal from regions of dense dark matter
  - Galactic center
  - Dwarf galaxies

Detecting Dark Matter



- Look for missing momentum in particle accelerators



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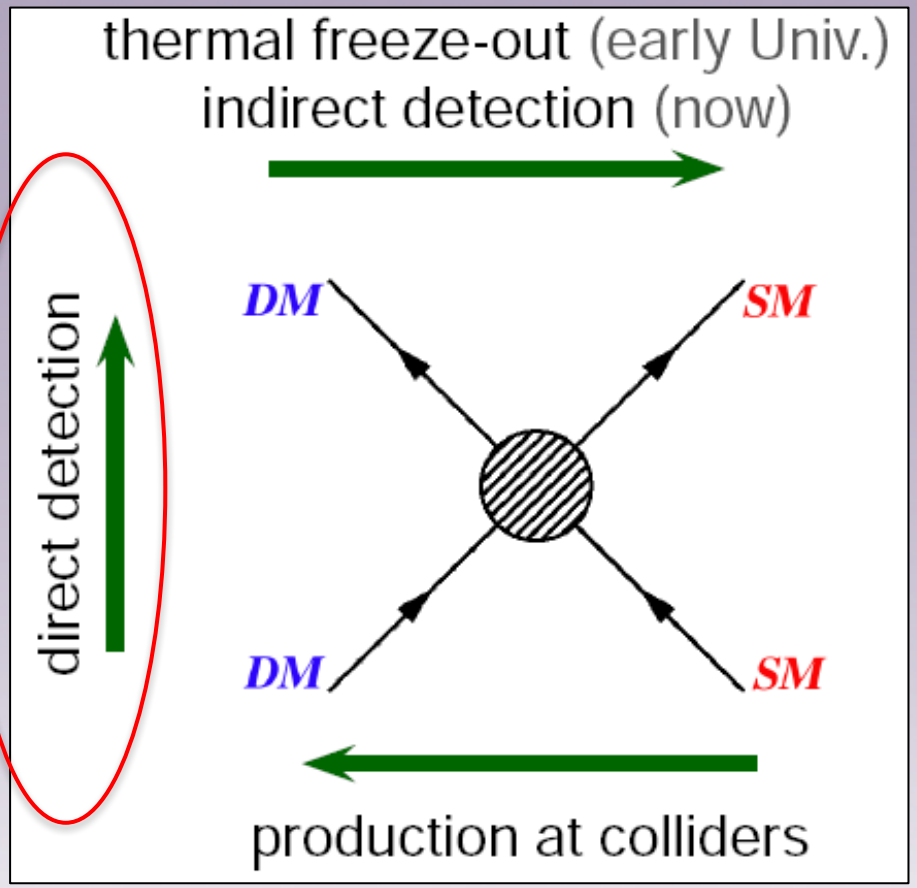
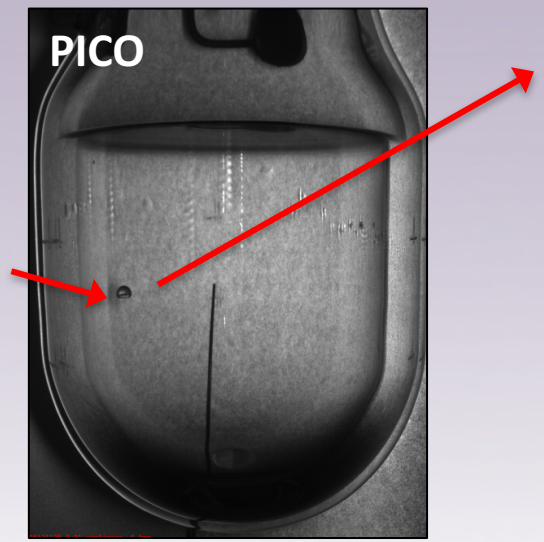


- Look for energy deposition of dark matter scattering on detector nucleii



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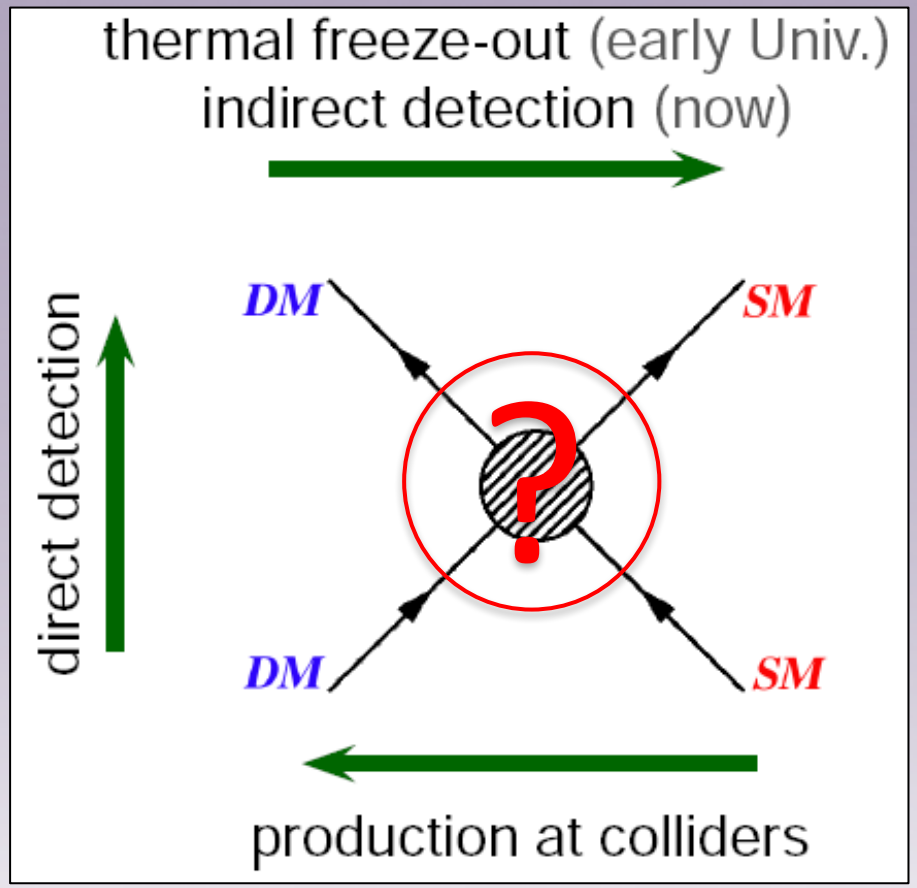

- Exact interaction is unknown…
- How does the WIMP interact with the nucleus?

spin-independent
Heavy targets (Xe, Ar, I)

spin-dependent
Light targets with unpaired nucleon (F, H)

PICO

Bubble Chambers

located in SNOLAB

PICO-2L

100 kg-day exposures

PICO-60

ton-day exposures

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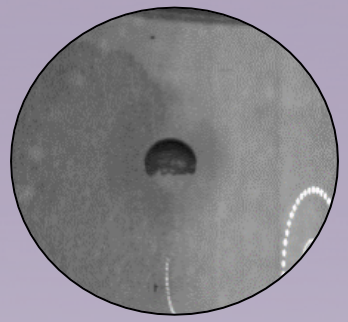
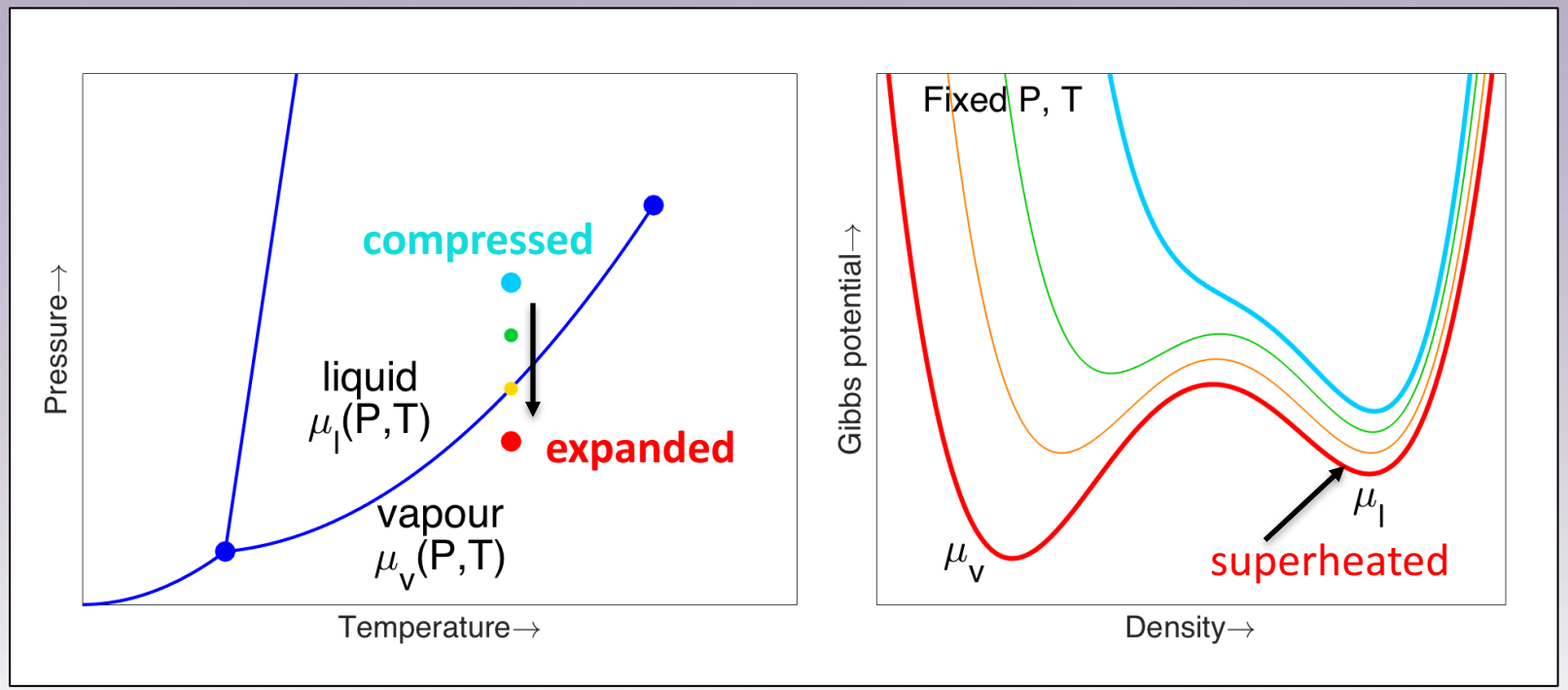
Basic Principles

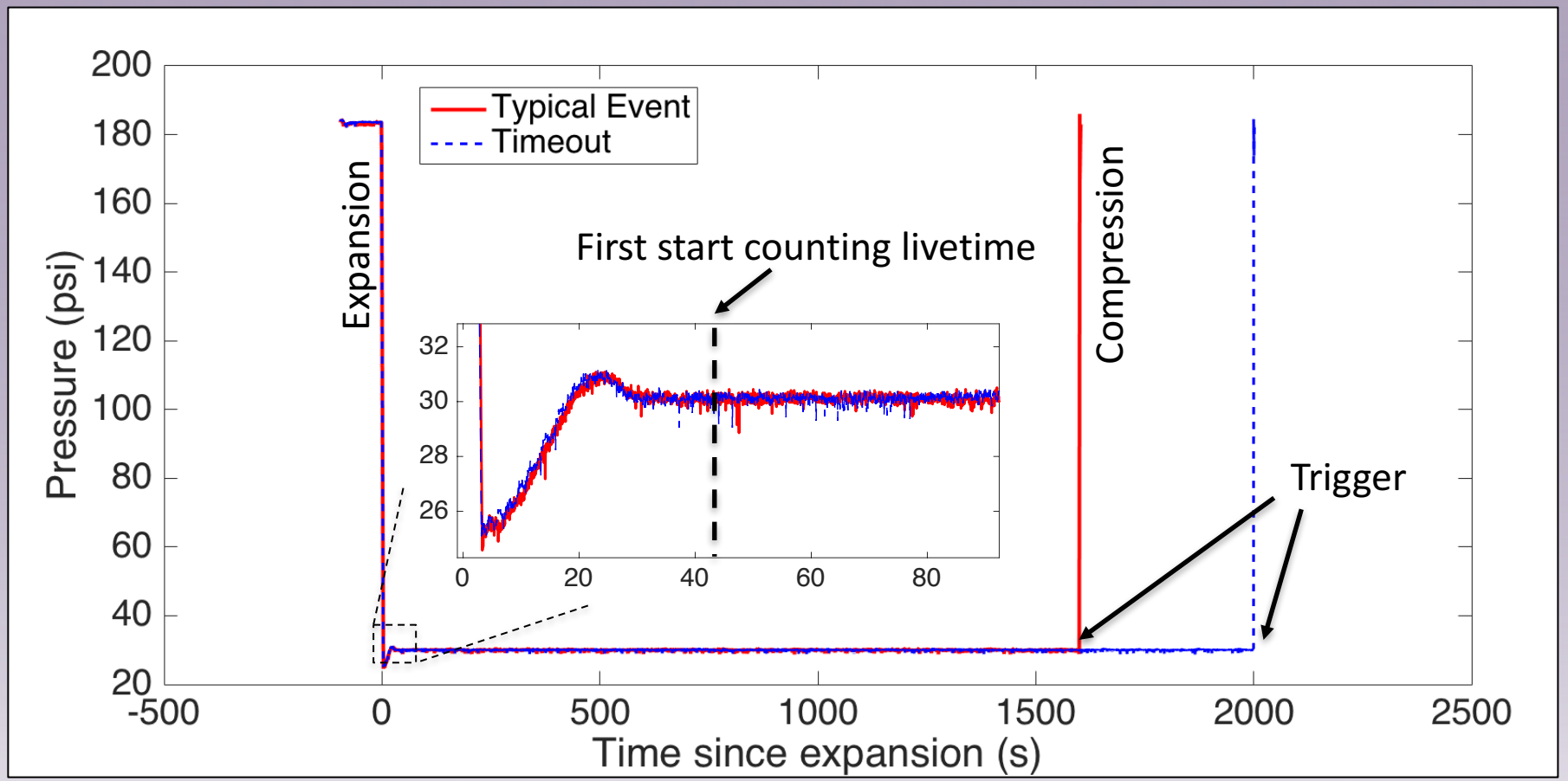
- Superheat a fluid by lowering pressure
- Wait for energy deposition in metastable state
- Interaction nucleates small gas pocket that grows
- Trigger on bubble with cameras





plots courtesy of Eric Dahl

Detector Event Cycle



- Primary optical trigger (look for change in images)
- Timeout trigger at 2000s (improves stability)

Bubble Chamber Event

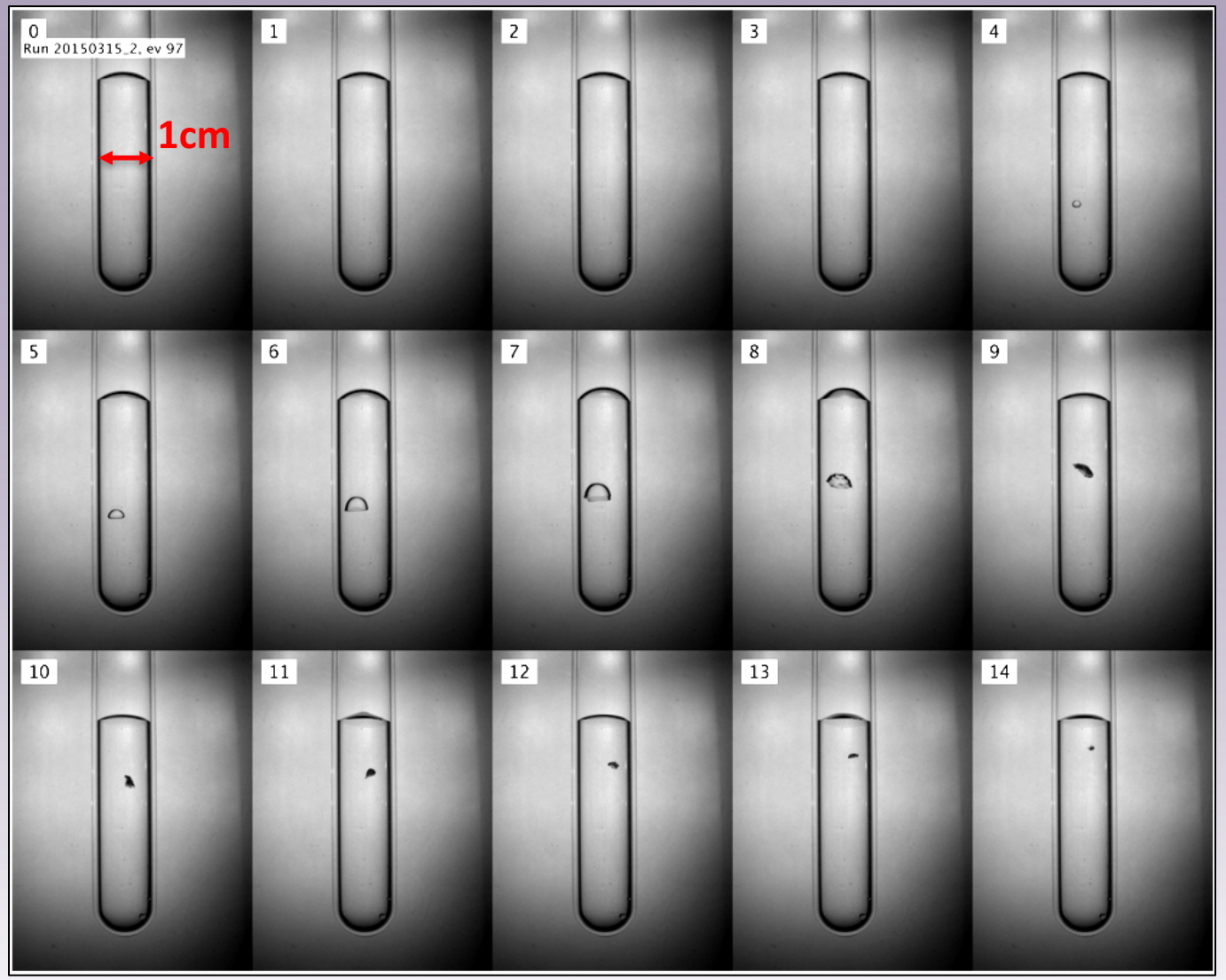
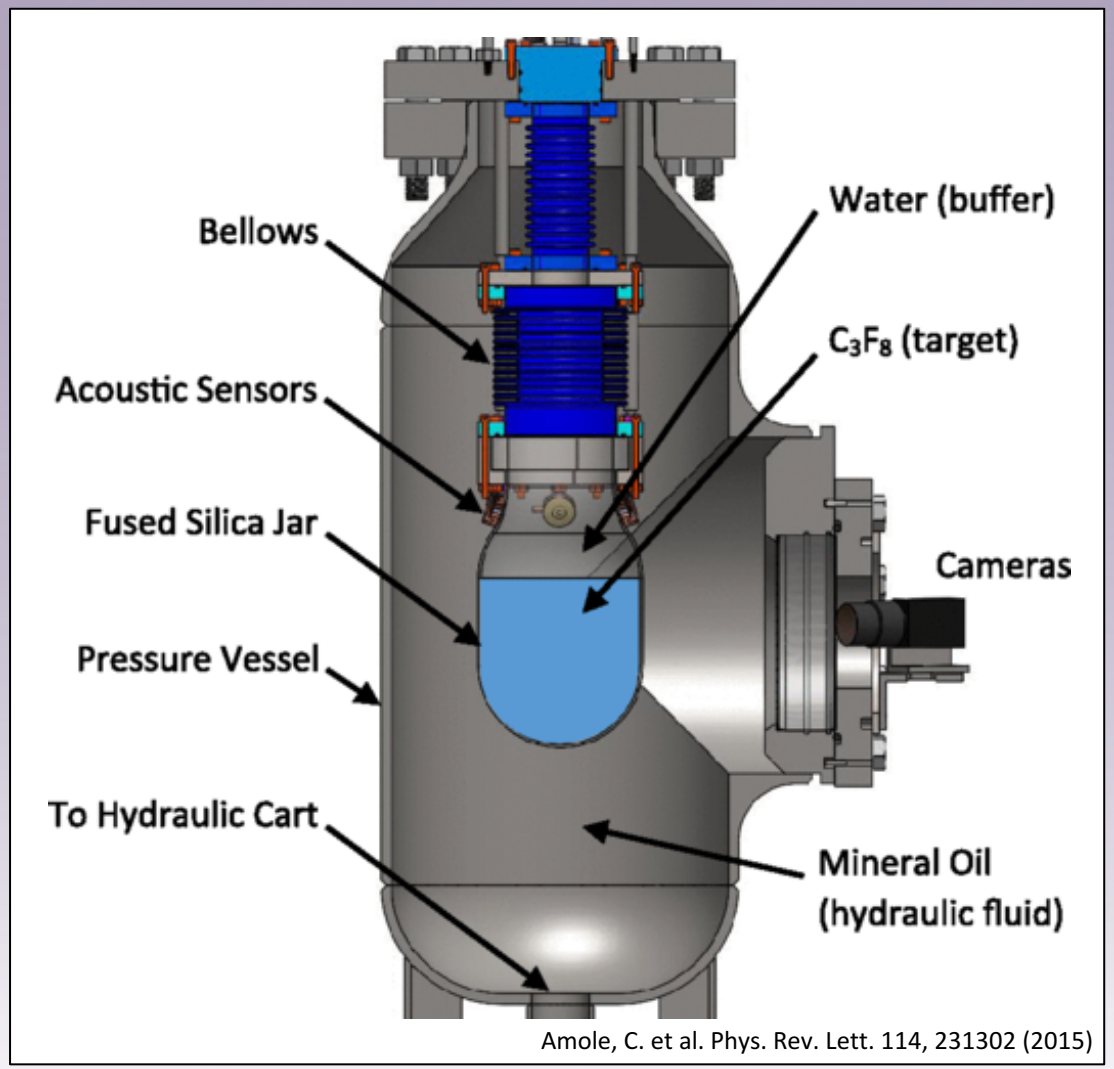


photo credit Guillaume Giroux

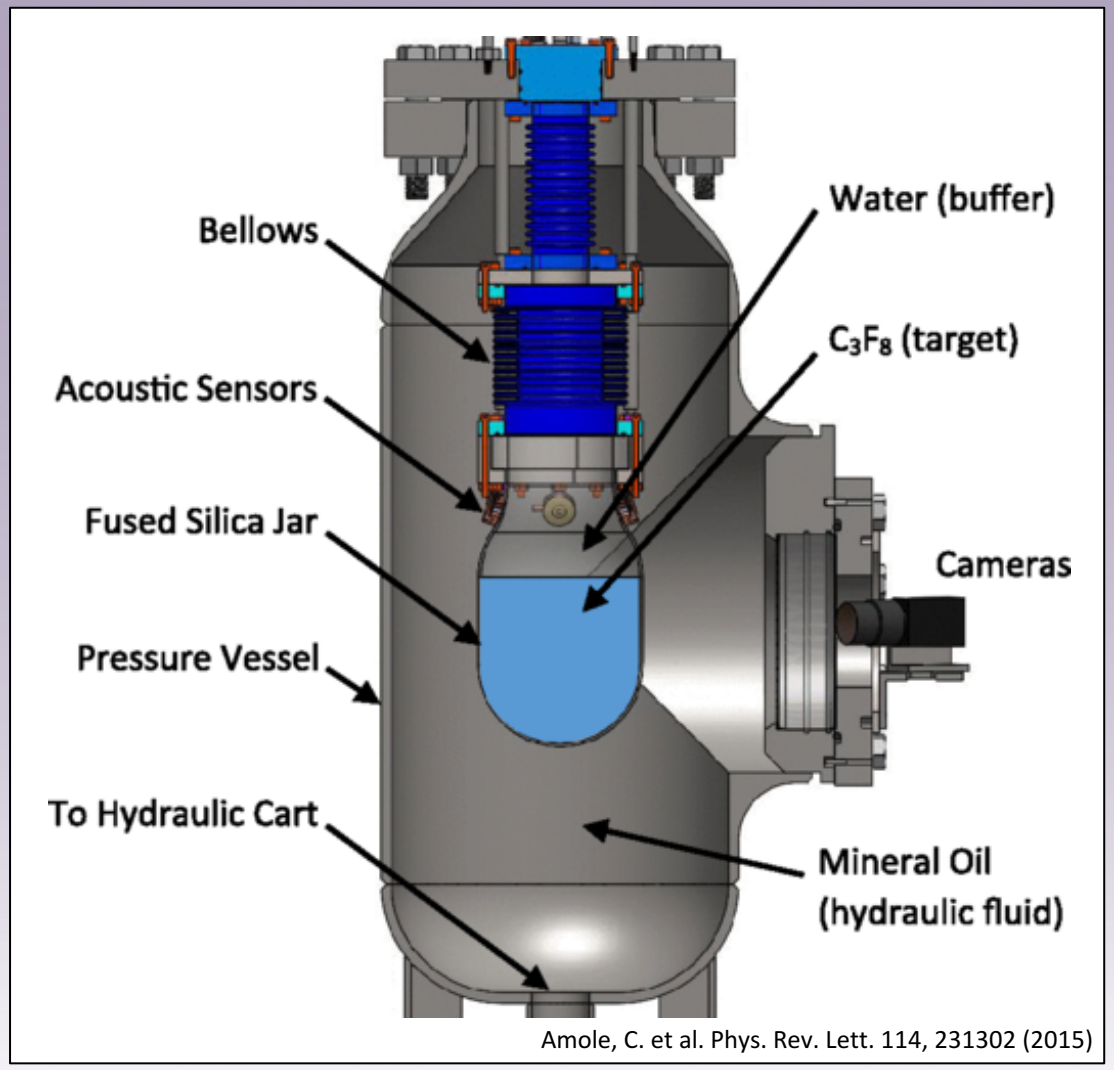
Bubble Chamber Design



Amole, C. et al. Phys. Rev. Lett. 114, 231302 (2015)

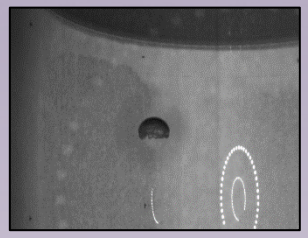
- Pressure control of hydraulic outer volume
- Bellows transmit pressure to inner fluids
- Buffer liquid (water) separates active liquid (C_3F_8, CF_3I) from radioactive detector materials
- Active liquid sits in radio-pure quartz jar

Bubble Chamber Design

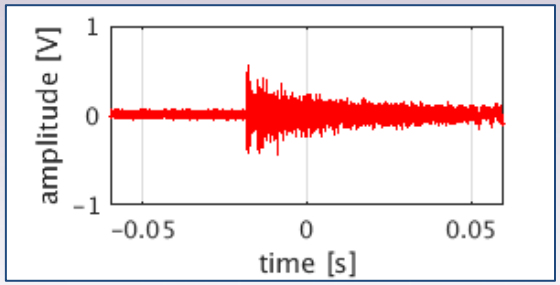


Amole, C. et al. Phys. Rev. Lett. 114, 231302 (2015)

- Cameras monitor for bubble nucleation with LED illumination



- Piezoelectric acoustic sensors listen for the bubble



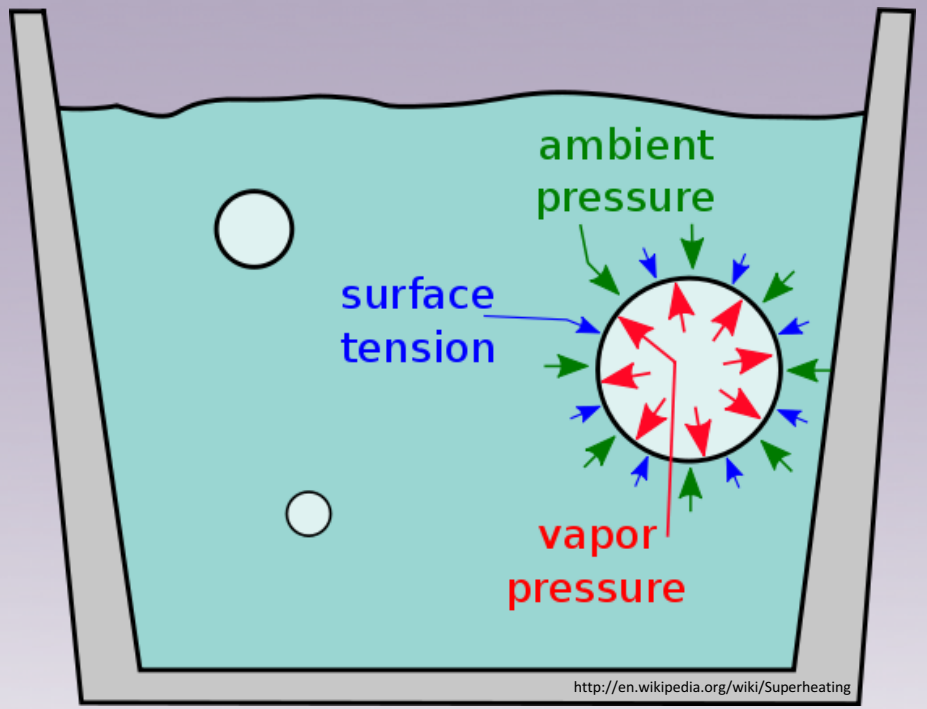
Threshold Determination

- Critical radius set by fluid properties and run conditions

$$P_v - P_l \geq \frac{2\sigma}{r_c}$$

- Critical radius determines energy threshold

$$E_T = E(T, P, fluid)$$



Threshold Calculation

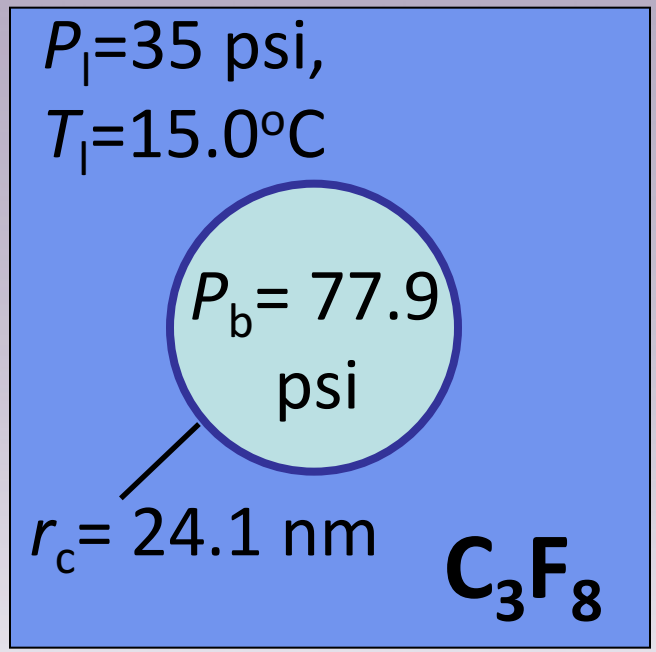
Surface energy, Bulk energy, Reversible Work

$$E_T = 4\pi r_c^2 \left(\sigma - T \left(\frac{\partial \sigma}{\partial T} \right)_\mu \right)$$ 1.57 keV

$$+ \frac{4\pi}{3} r_c^3 \rho_b \left(h_b - h_l \right)$$ 1.95 keV

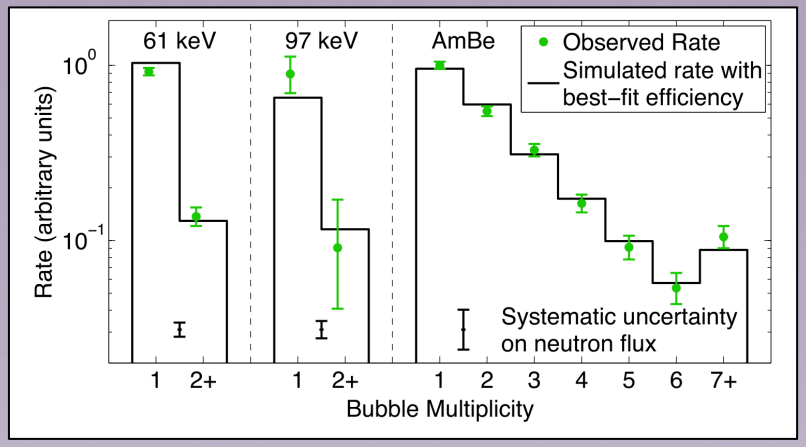
$$- \frac{4\pi}{3} r_c^3 \left(P_b - P_l \right)$$ -0.15 keV

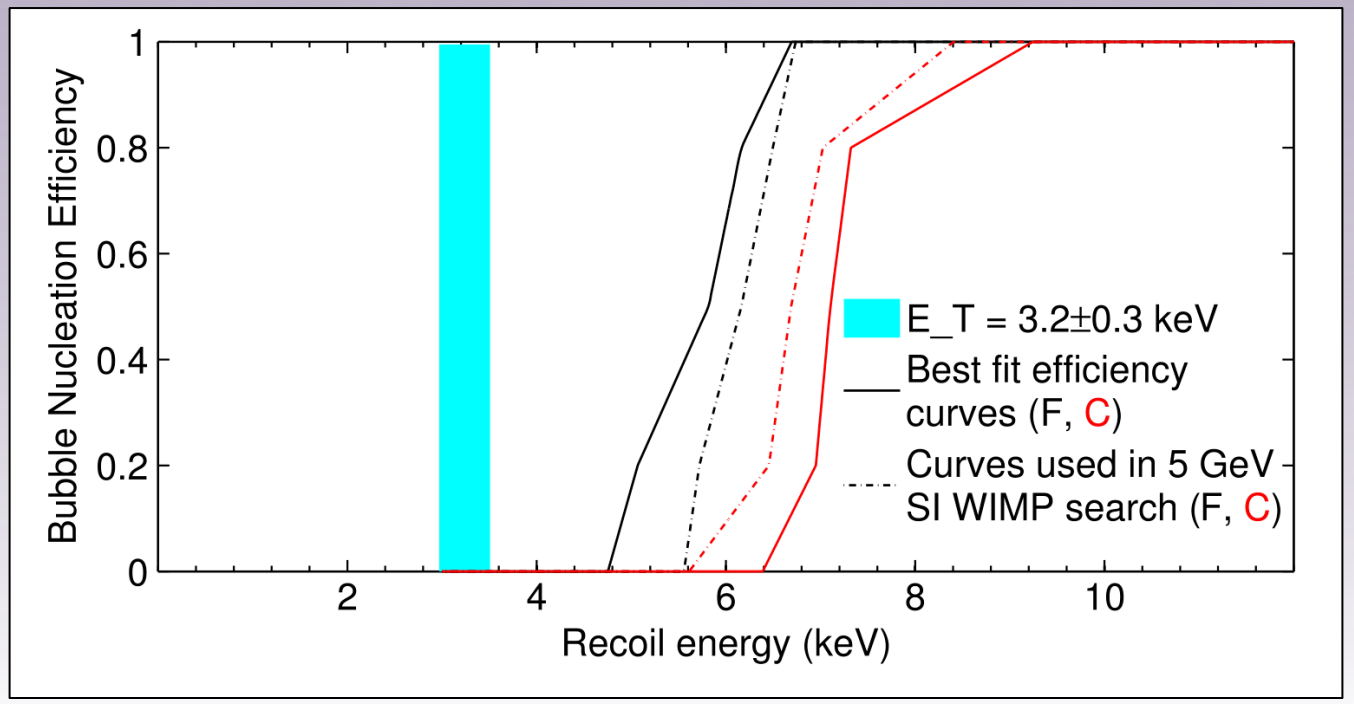
= 3.37 keV



Nuclear Recoil Efficiency

- Use neutrons to determine nucleation efficiency from nuclear recoils
- Full paper is in preparation





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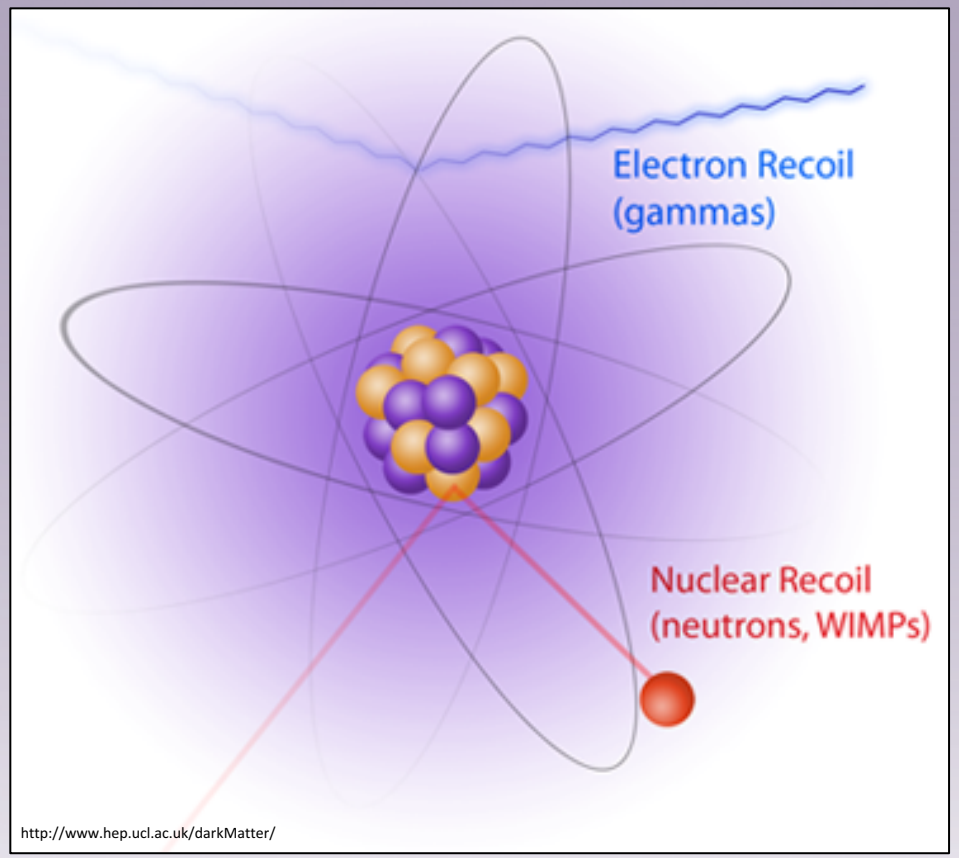
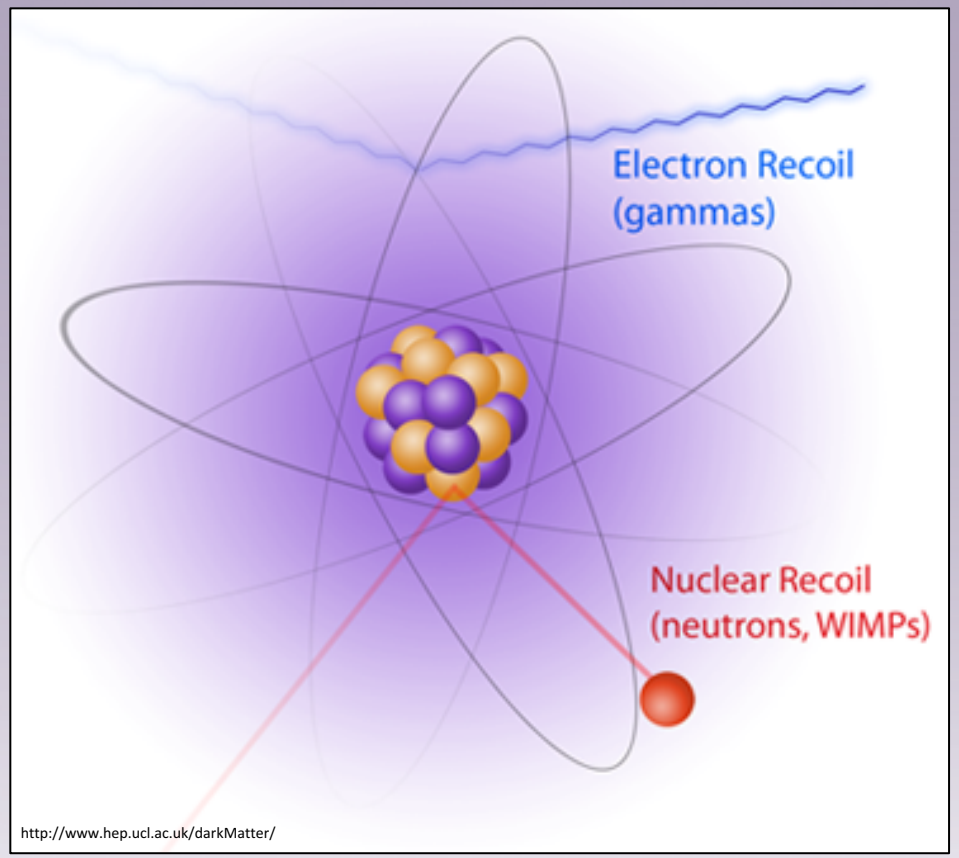


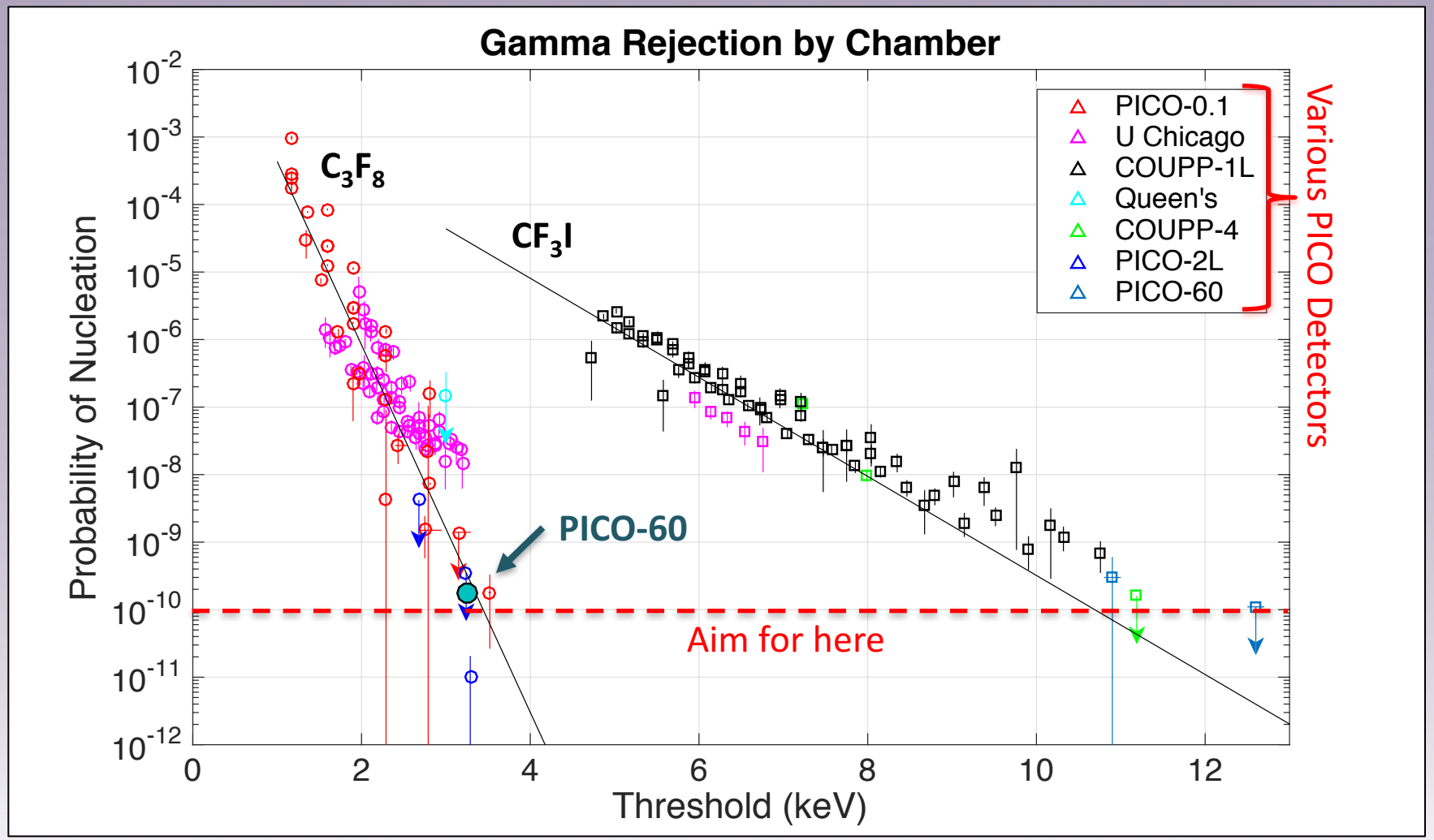
Detector Backgrounds

- Looking for dark matter interaction rates at order 1 event per tonne-day
- Detector is WAY more radioactive than that…
- Need to be able to reject radioactive backgrounds

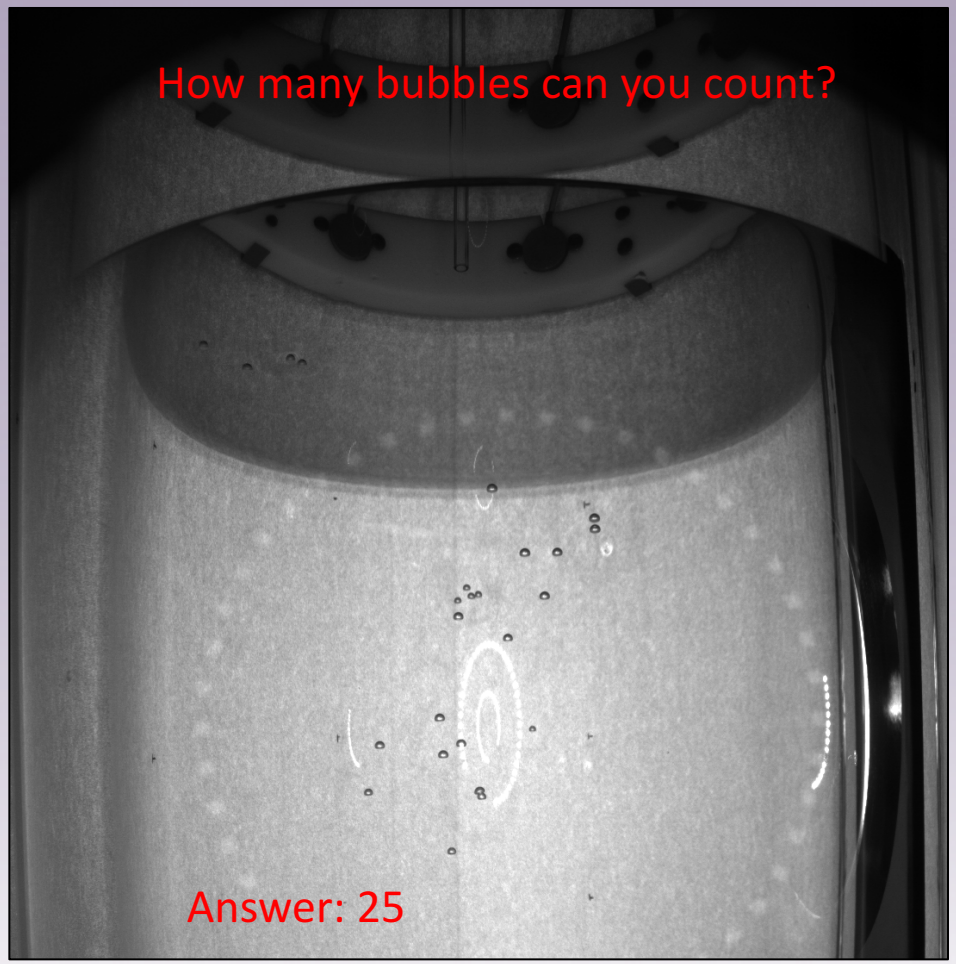


Gamma/Beta Backgrounds

Our detectors have a dE/dx threshold (E_T/r_c) that we get to set



Neutron Backgrounds

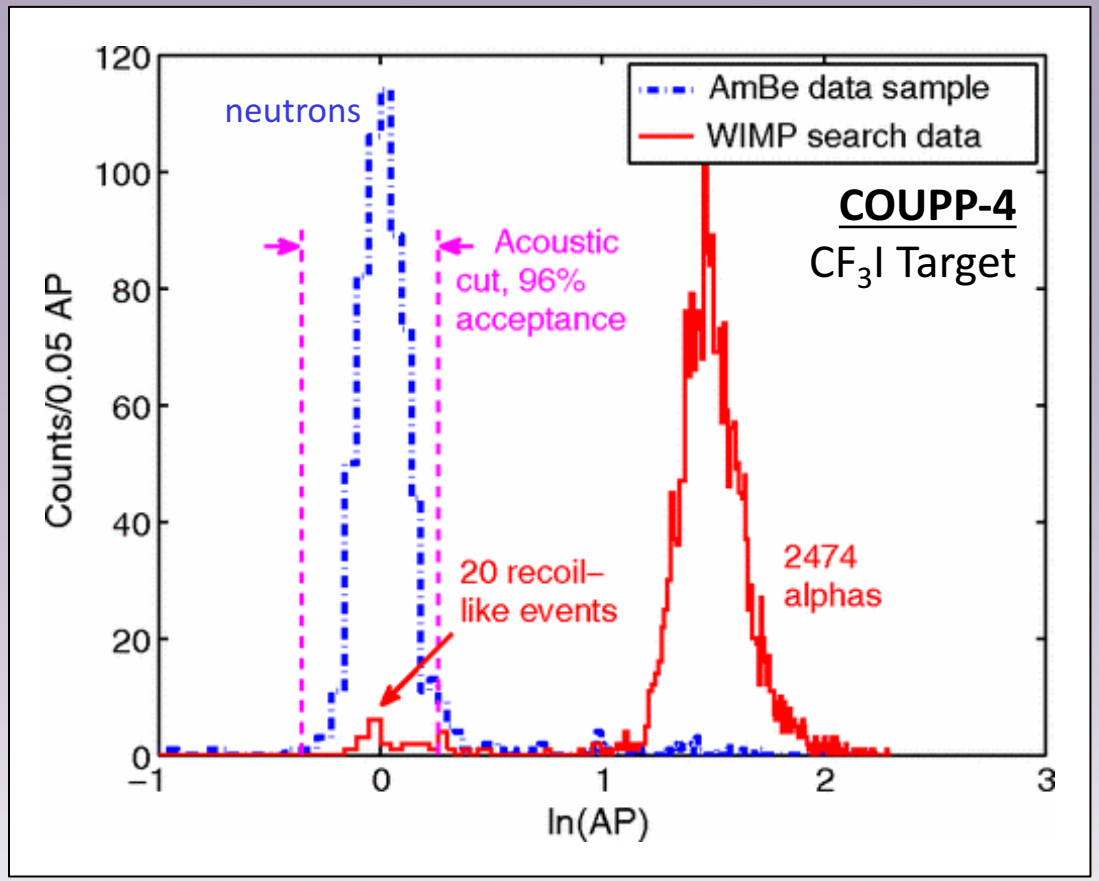


- Preferentially Multiple-scatter
  - Allows us to measure background rate directly
- Simulation tells us to expect 3:1 multiples to singles ratio
- Dominated by detector materials

Alpha Decay Backgrounds

- Measure the acoustic power of an event to construct AP (acoustic parameter)

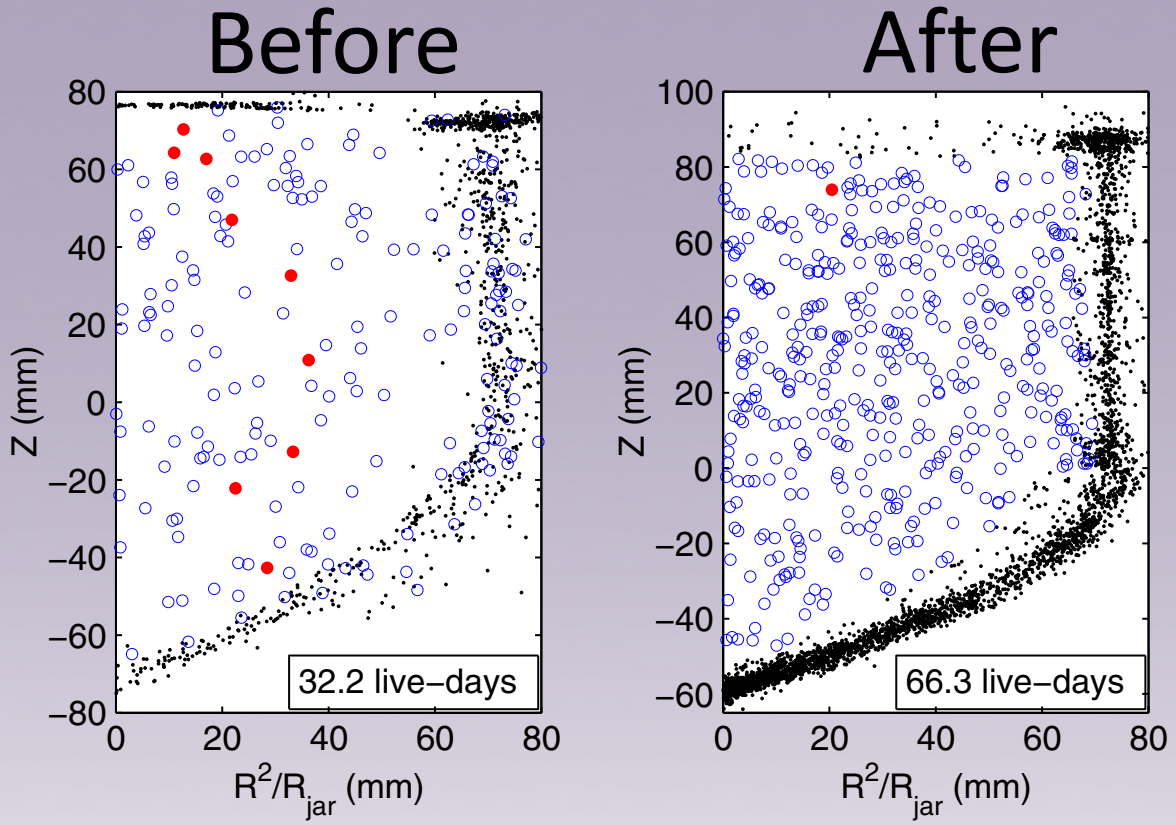
- Three populations:
  1. Neutrons *(Normalize AP to nuclear recoil signature)*
  2. Alphas are louder!
  3. Recoil-like background…



E. Behnke *et al*. Phys. Rev. D 86, 052001 (2012)

Anomalous Background

- PICO-2L Run1
  - 9 candidate events in 32 live-days at 3.2keV
  - **Inconsistent with known radioactive backgrounds AND dark matter**
- PICO-2L Run2
  - 1 candidate event in 66 live-days at 3.2keV
  - **Consistent with neutron expectations**
- Between runs, the detector was cleaned of particulate contamination

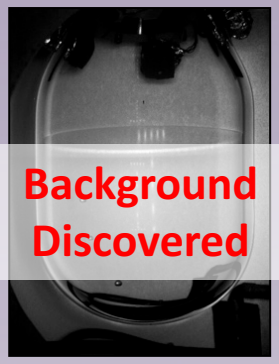


C. Amole *et al*. Phys. Rev. D 93, 061101(R) (2016)

Hypothesis: combination of particulate matter and water leads to anomalous nucleation mechanism

PICO Timeline

COUPP-4 (2011)
CF_3I Target



Background Discovered

Try switching target fluids

PICO-2L (2014)
C_3F_8 Target

Background Limited

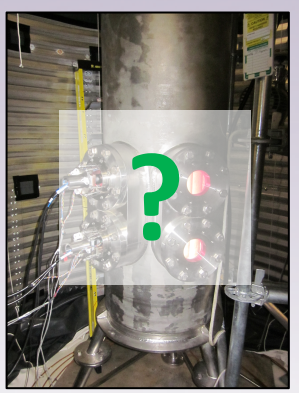
Try removing particulate

PICO-2L (2016)
C_3F_8 Target

Neutron Limited!

Try scaling

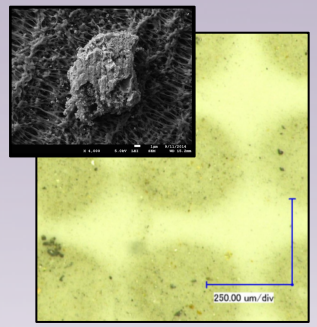
PICO-60 (2017)
C_3F_8 Target



Try scaling to increase statistics

PICO-60 (2014)
CF_3I Target

Background Limited



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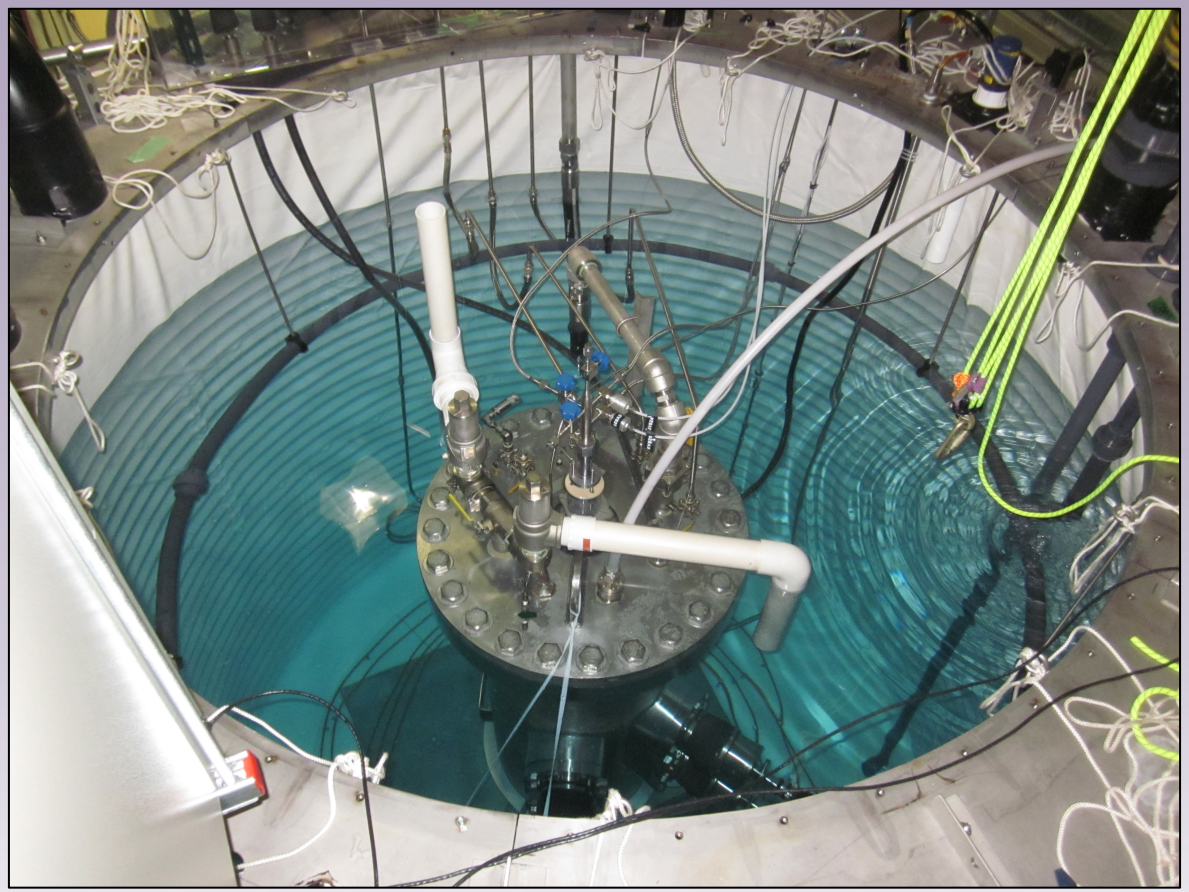
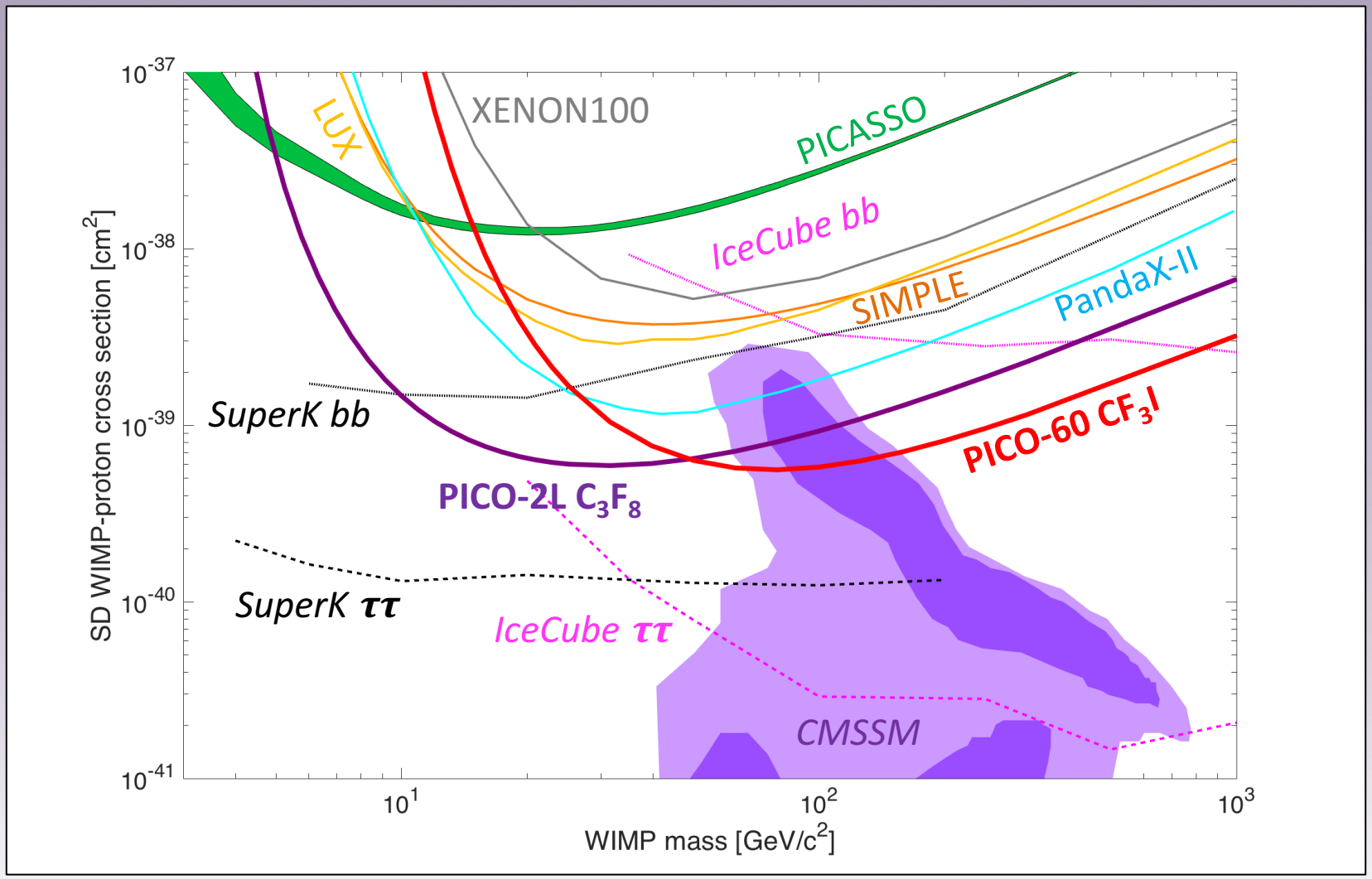
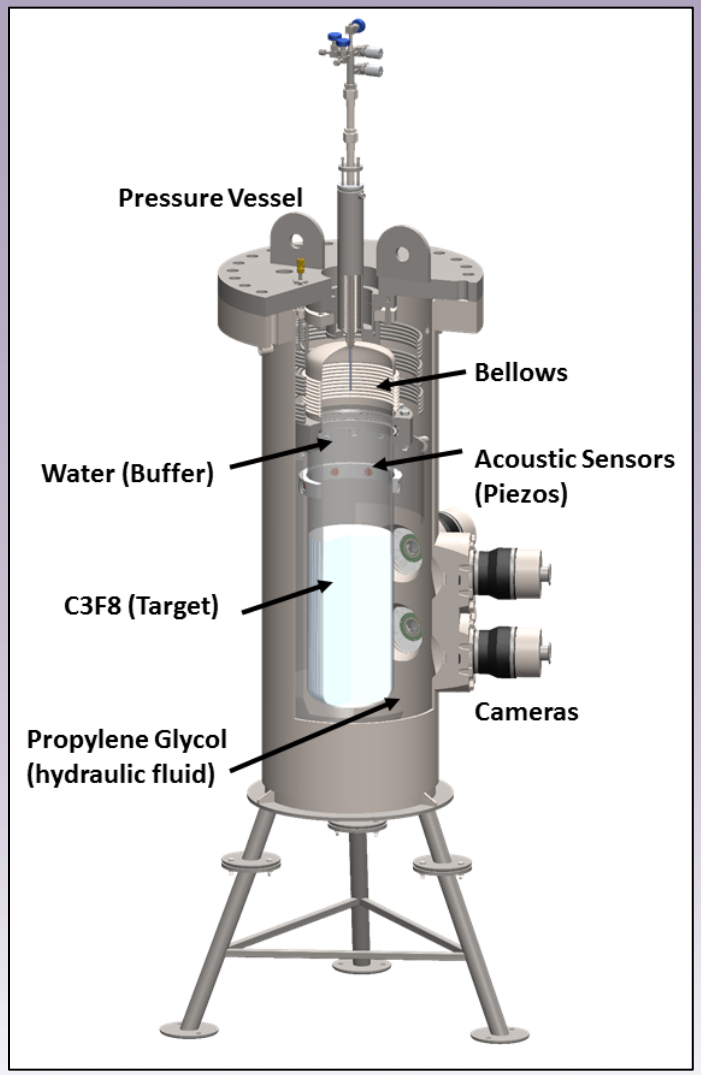


Previous Results

Spin-dependent WIMP-proton coupling



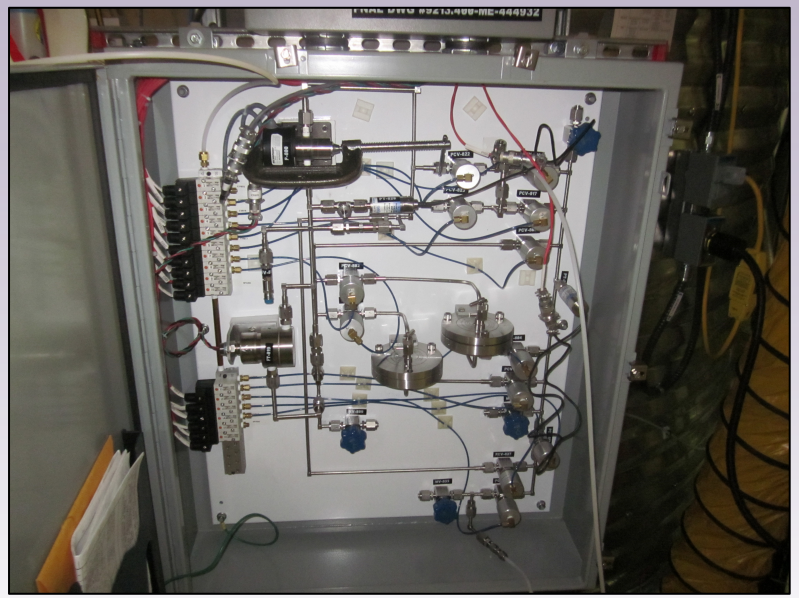
PICO-60 Design



- Piston pressure control
- 4 cameras monitoring active liquid
- 8 piezoelectric acoustic transducers
- Located 6800ft underground in SNOLAB
- Entire pressure vessel submerged in water tank
  - Temperature control
  - Neutron shielding

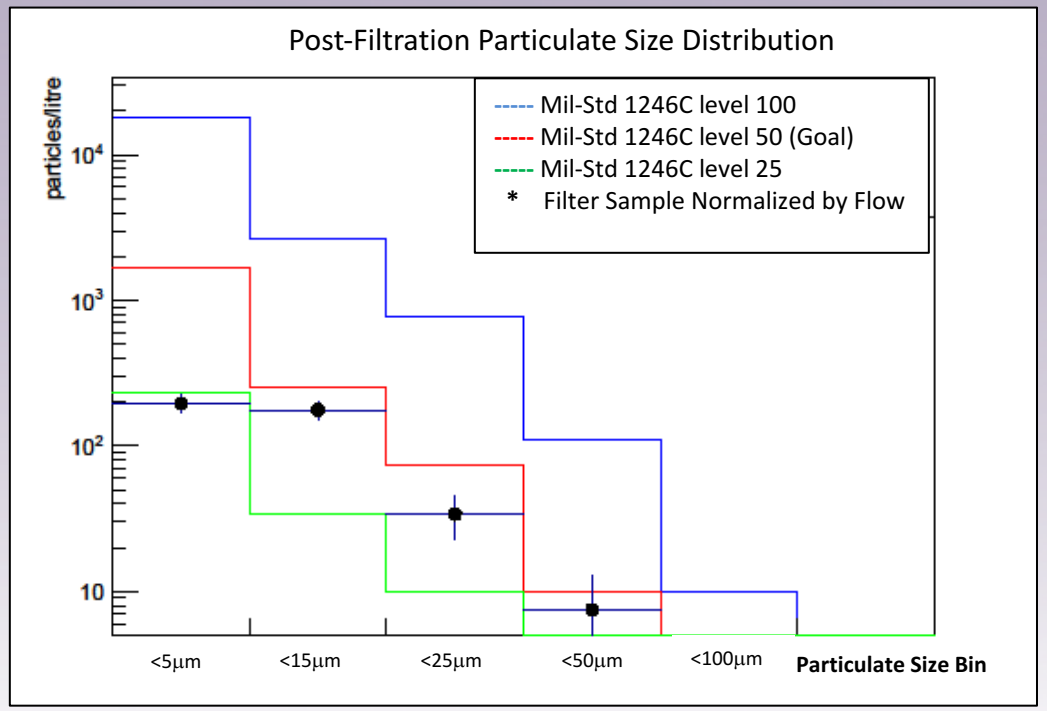
PICO-60 Upgrades

- New water system for improved thermal control
- Filtration system allows in-situ buffer sampling
- Non-abrasive PTFE seal
- Four cameras allow larger volume

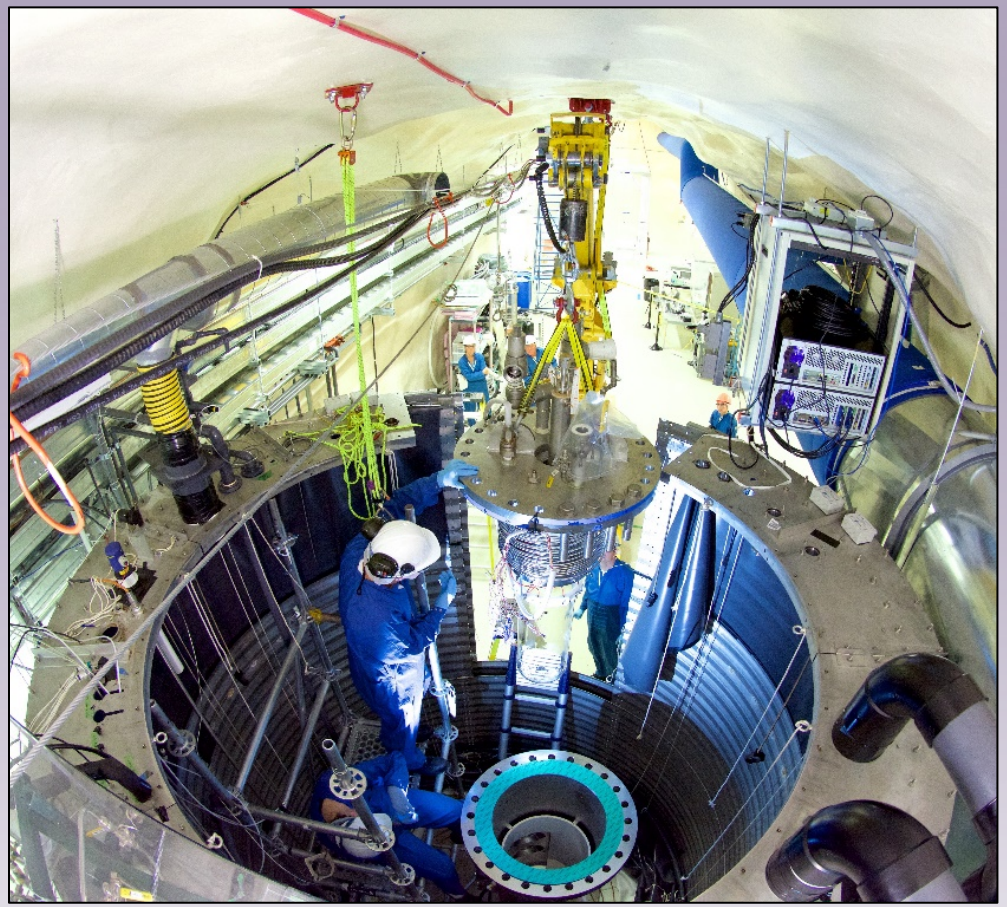


PICO-60 Cleaning

- Every component touching the inner volume was cleaned against MIL-STD-1246C level 50



Commissioning



- Filled with 40L C_3F_8 on June 30, 2016

What do we measure?

- Camera images (primary trigger)
  - Was there a bubble (Y or N)? **Electron Recoil Rejection**
  - How many bubbles were there? **Neutron Rejection**
  - What were the bubble positions? **Surface Rejection**
- Temperature
- Pressure (secondary trigger)

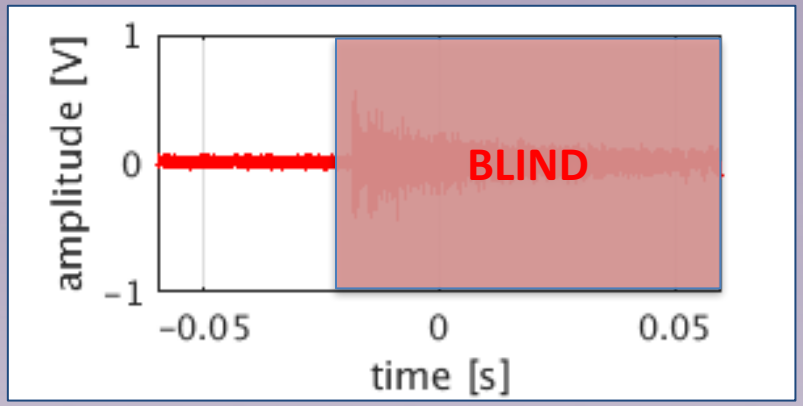
Threshold Determination

- Acoustic signal **Alpha (radon) Rejection**

Blind this information

Blinding a bubble chamber

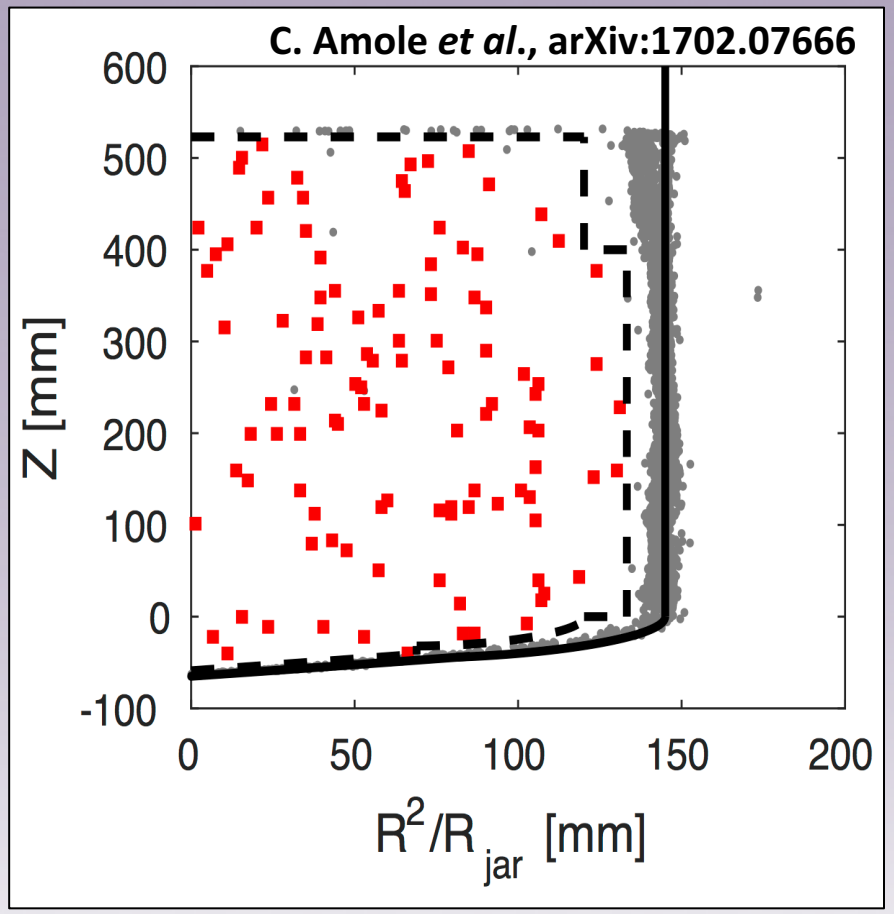
- First time this has been done for PICO
- Alpha decays (from radon) are only distinguishable from candidate events acoustically



- Blinding acoustics effectively salts your data with alpha decays
  - Unblinding acoustic information removes the salt
- **Blinding scheme: define ALL cuts and efficiencies using non-WIMP search data BEFORE looking at the acoustic information**
  - Acoustic cuts based on neutron calibration data
- We calibrate the detector before and after WIMP search to check for consistency

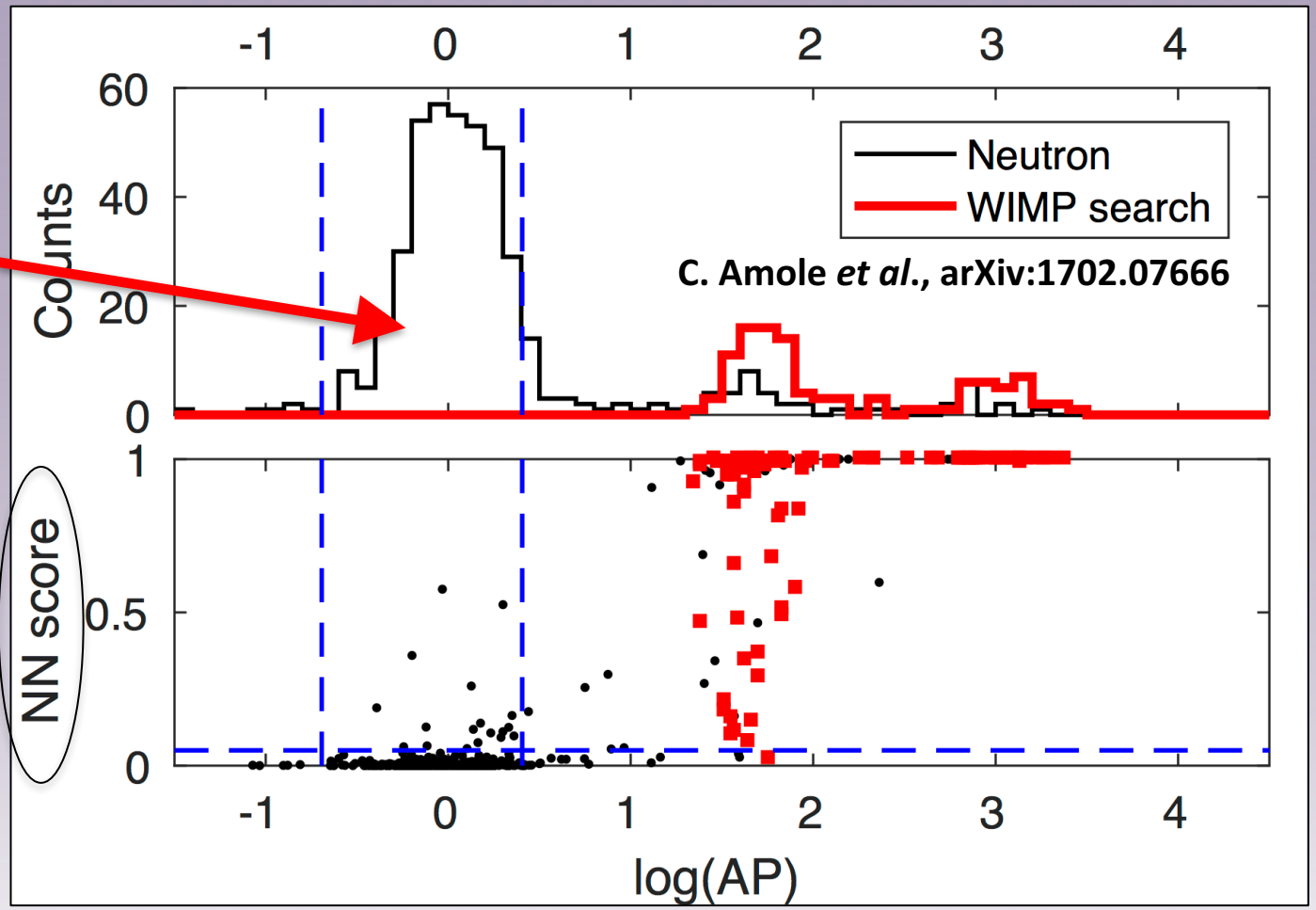
Before Opening the Box

- 106 bulk singles in WIMP search dataset
  - *Acoustics Still Blind*
  - Consistent with Rn decay rate in pre-WIMP search unblinded data
- Neutron Background
  - Not blinded to multiplicity
  - 3 multiple bubbles in the physics data
  - Multiples to singles ratio is approximately 3:1 from calibration and simulation
- **Conclusion: 0-3 bulk singles would be consistent with neutrons and no anomalous background**



After Opening the Box

No events in signal region!



Neural Network Acoustic Analysis

- Not as good as AP, ***yet…***

PICO-60 Results

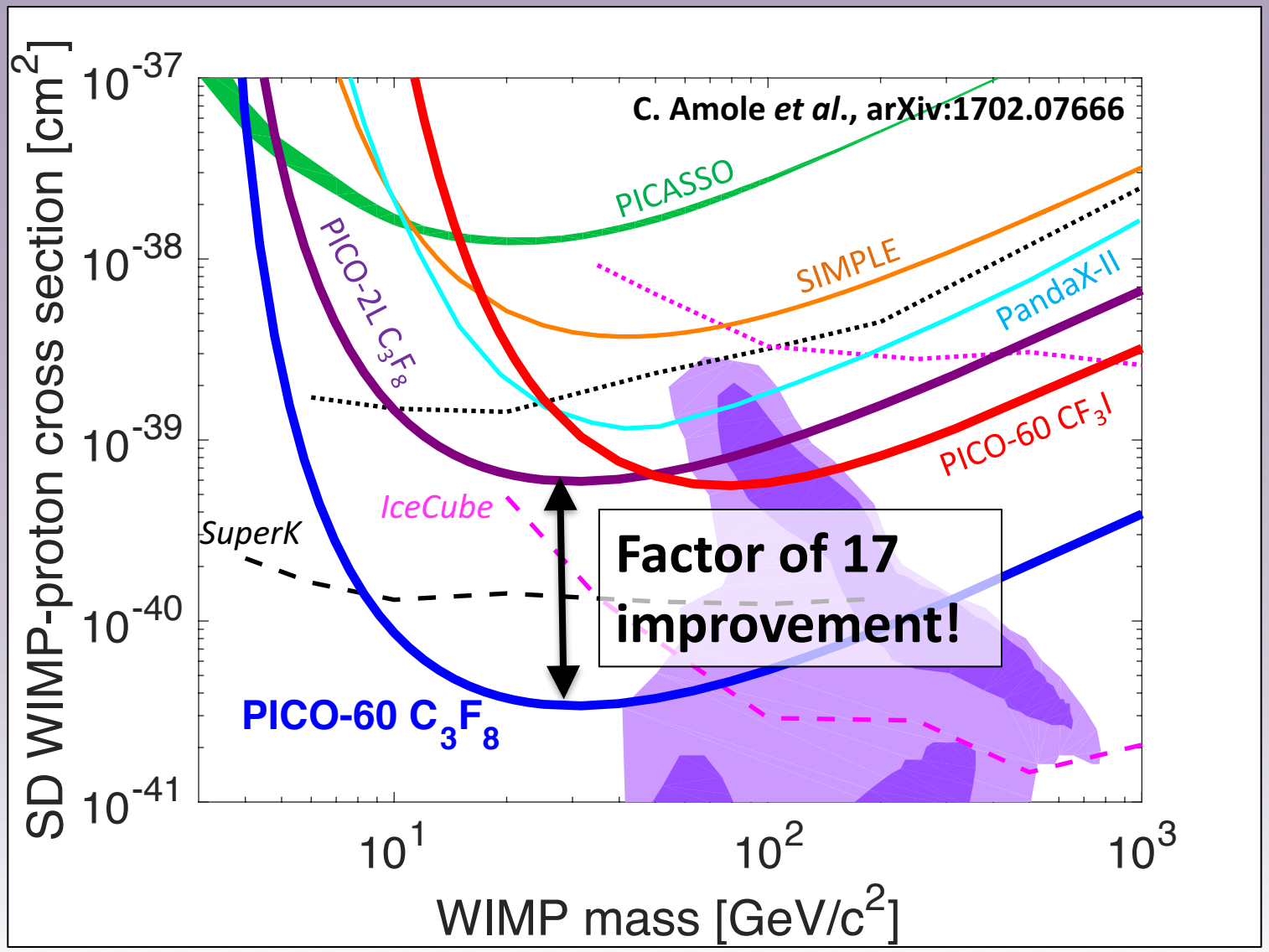
Dataset	Efficiency (%)	Fiducial Mass (kg)	Exposure (kg-days)	No. of events
Singles	85.1 ± 1.8	45.7 ± 0.5	1167 ± 28	0
Multiples	99.4 ± 0.1	52.2 ± 0.5	1555 ± 15	3

TABLE I. Summary of the final number of events and exposure determination for singles and multiples in the 30.0 live-day WIMP search dataset of PICO-60 C_3F_8 at 3.3 keV thermodynamic threshold.

C. Amole *et al.*, arXiv:1702.07666

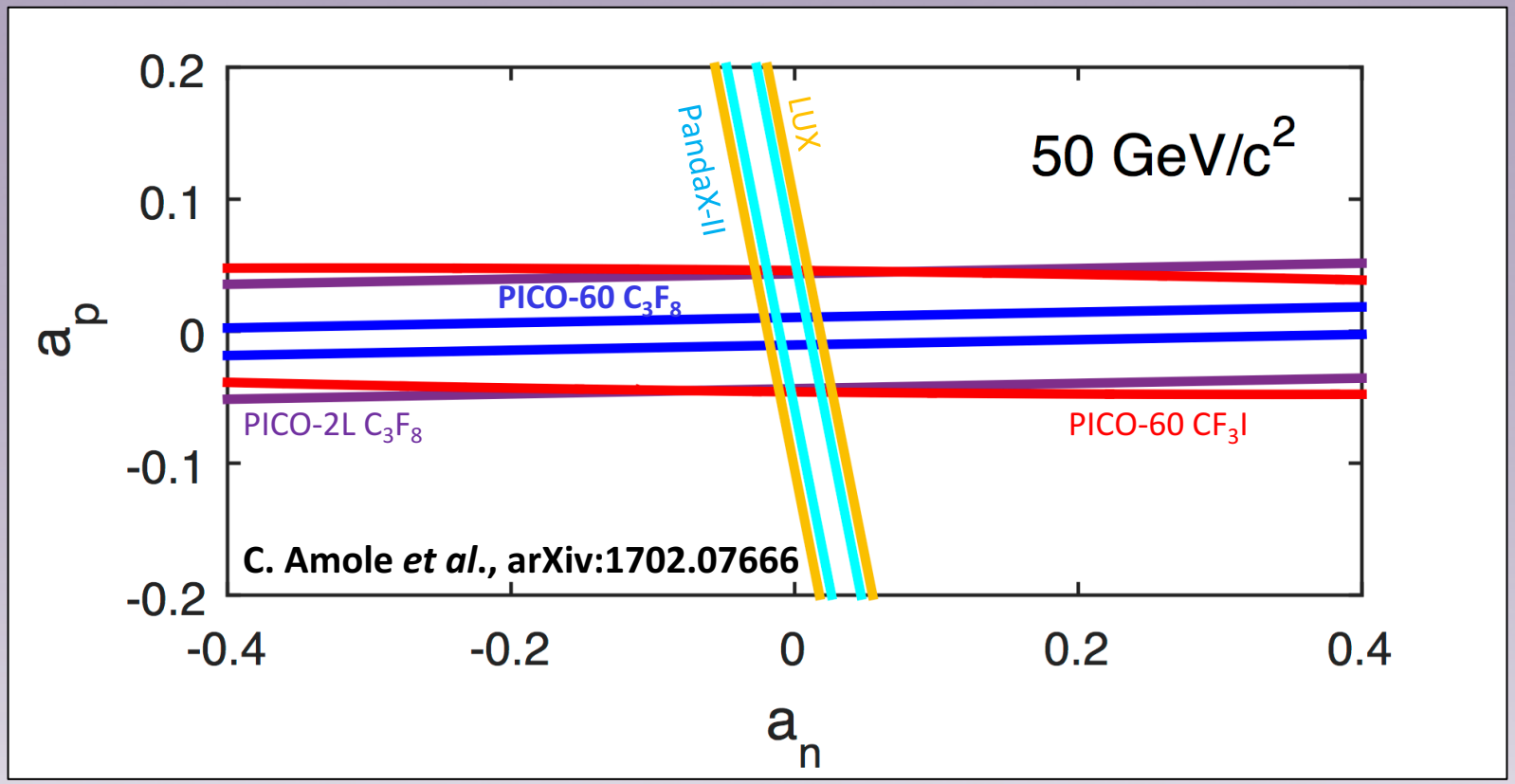
- Multiples efficiency is higher because no fiducial, acoustic cuts
- We simulate and measure a 3:1 ratio of multiples to singles for neutron calibration data
- **Of the 106 fiducial-bulk singles, none are consistent with nuclear recoil hypothesis (all are consistent with radon chain alphas)**

Spin-dependent Limits



Nucleon Coupling Limits

Consider spin-dependent coupling to proton and neutron



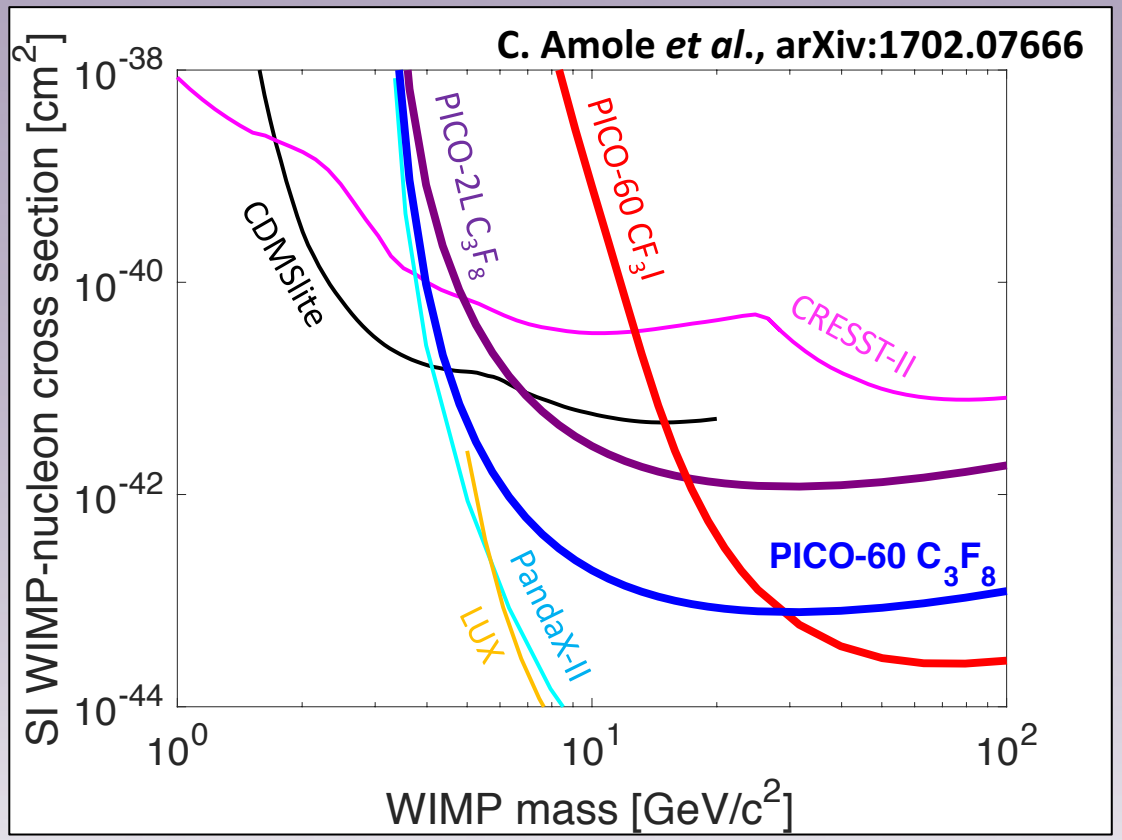
See Tovey for details:

D.R. Tovey, *et al.*, Phys. Lett. B 488, 17 (2000)

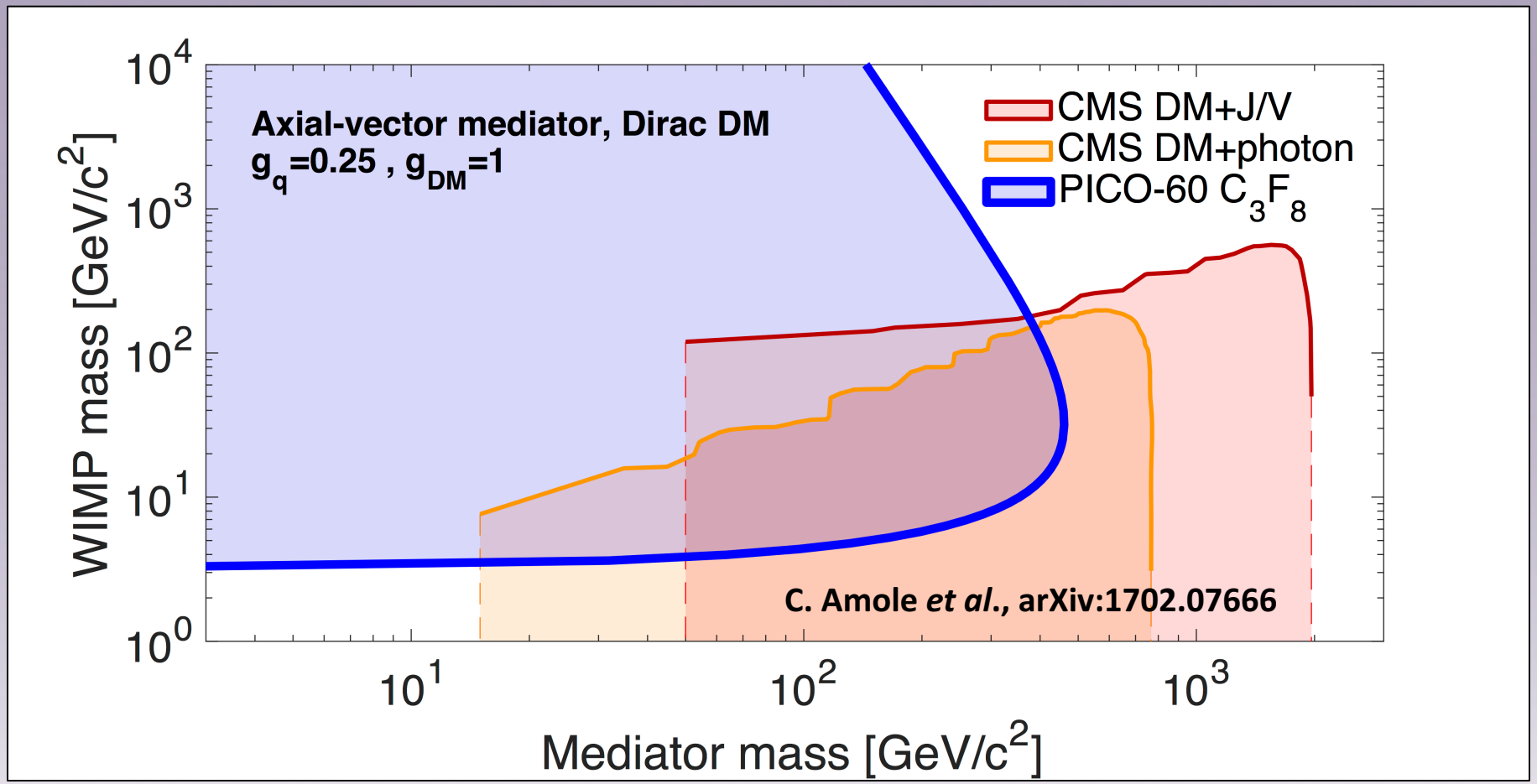
$$\sigma_A^p = \frac{32 G_F^2 \mu_A^2}{\pi} \left(a_p \langle S_p \rangle\right)^2 \frac{J+1}{J}$$

Spin-independent Limits

- Light nuclear targets give sensitivity to low-mass WIMPs
- Unexplored phase space would be accessible with slightly reduced threshold



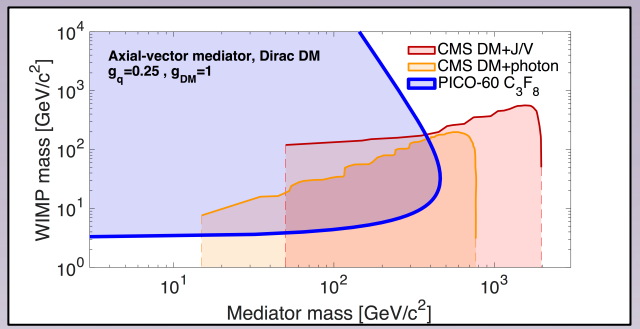
Comparison to Collider

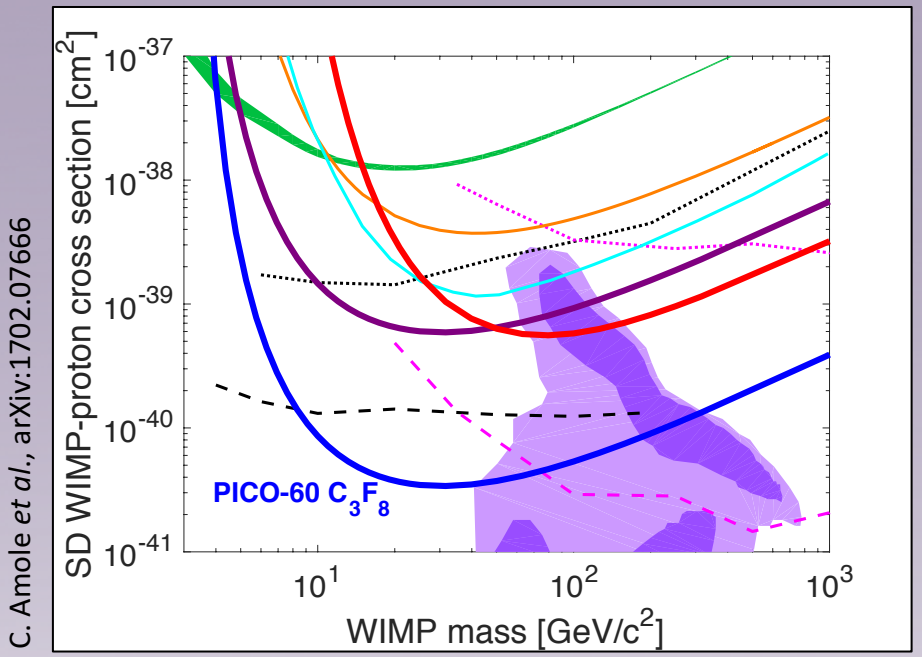


Idea: rather than try to plot model-dependent collider limits in our space, let's plot our limits on their model

PICO-60 Summary

- New, world-leading constraints on WIMP dark matter



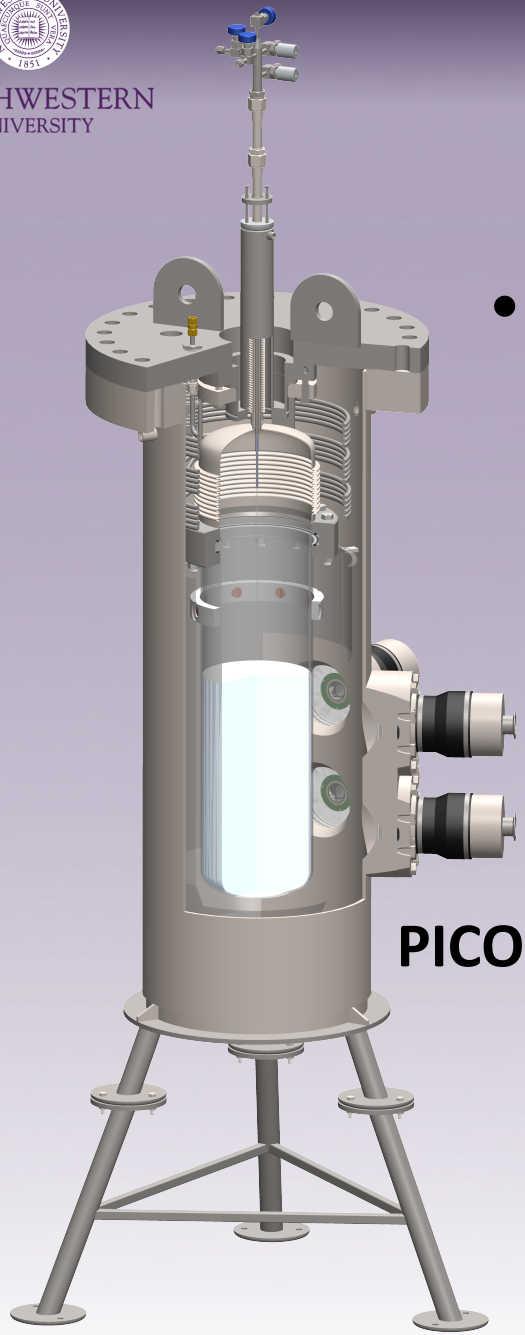


- **Question:** We have shown we can mitigate our anomalous background, but can we eliminate the background mechanism entirely?

Overview

1. Motivation
2. Bubble Chamber Physics
3. Backgrounds to Dark Matter
4. New Results from PICO
5. PICO Future Plans

PICO-40L



PICO-60

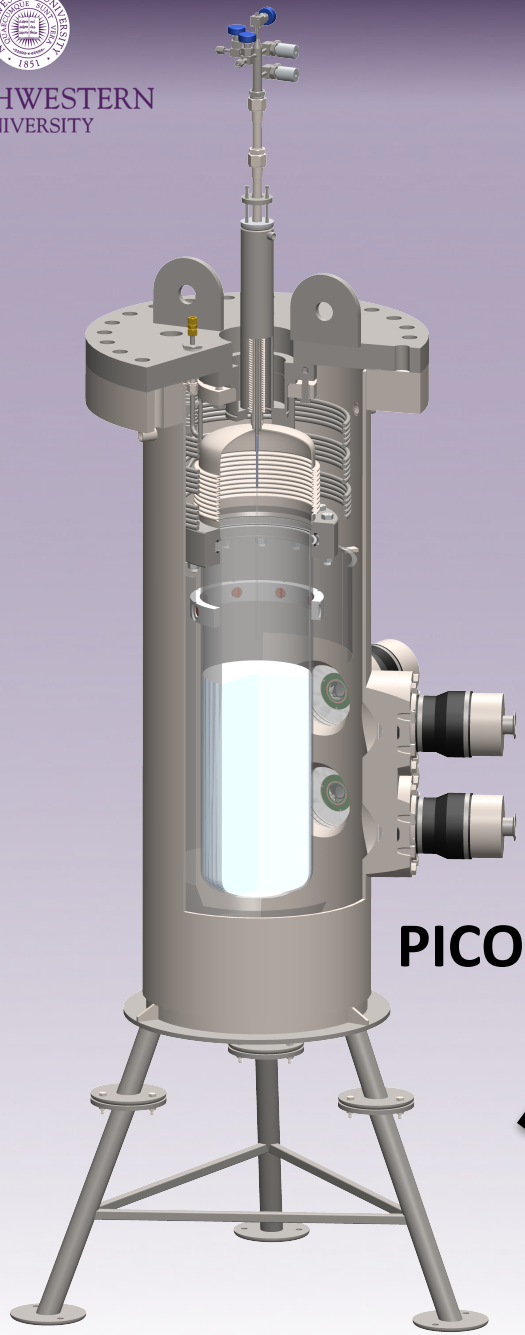
- We have shown we can mitigate our anomalous background, but can we eliminate the background mechanism entirely?

IDEA: Eliminate buffer fluid

- Purpose of buffer liquid is to isolate the active liquid from the stainless parts
- Elimination of buffer liquid would allow in-situ purification of active liquid

PICO-40L

Eliminate buffer fluid

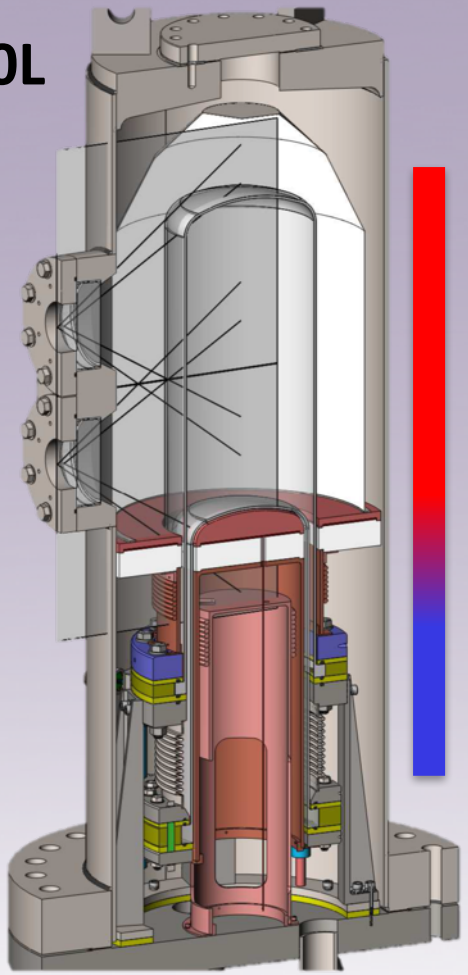


PICO-60

Purpose of buffer liquid is to isolate the active liquid from the stainless parts

PICO-40L

Thermal gradient can ensure that target fluid near stainless parts is not active

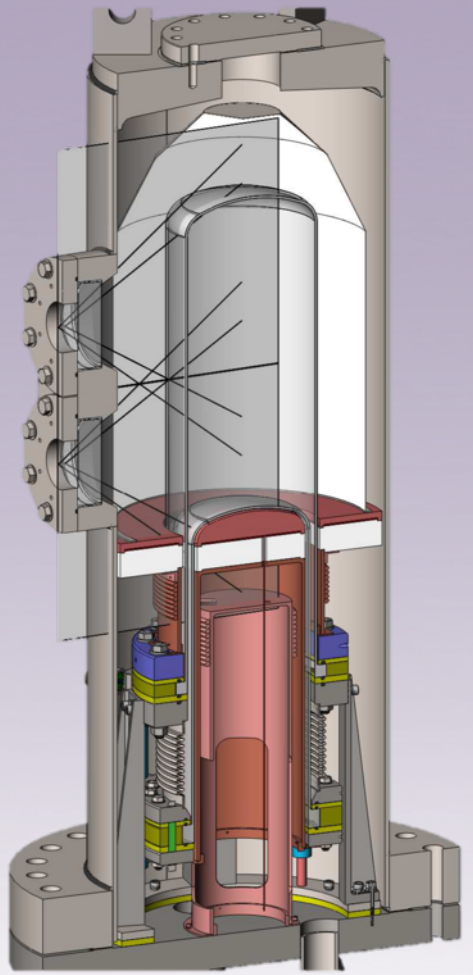


Thermal Gradient

PICO-40L

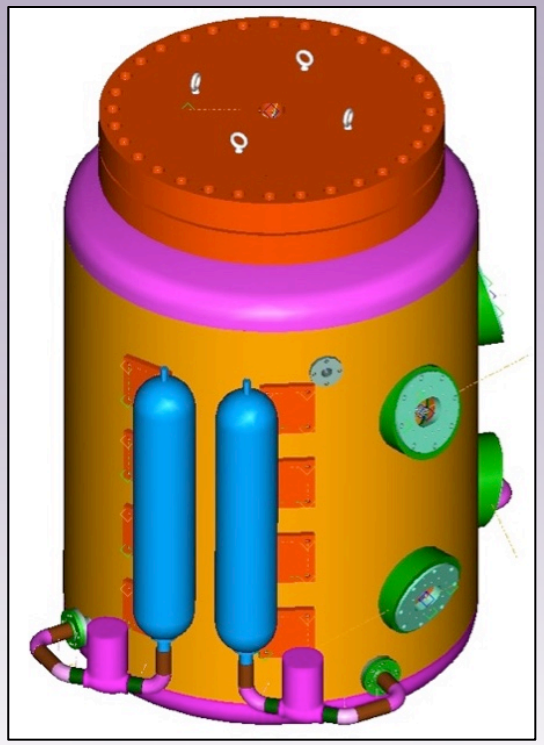
Physics reach

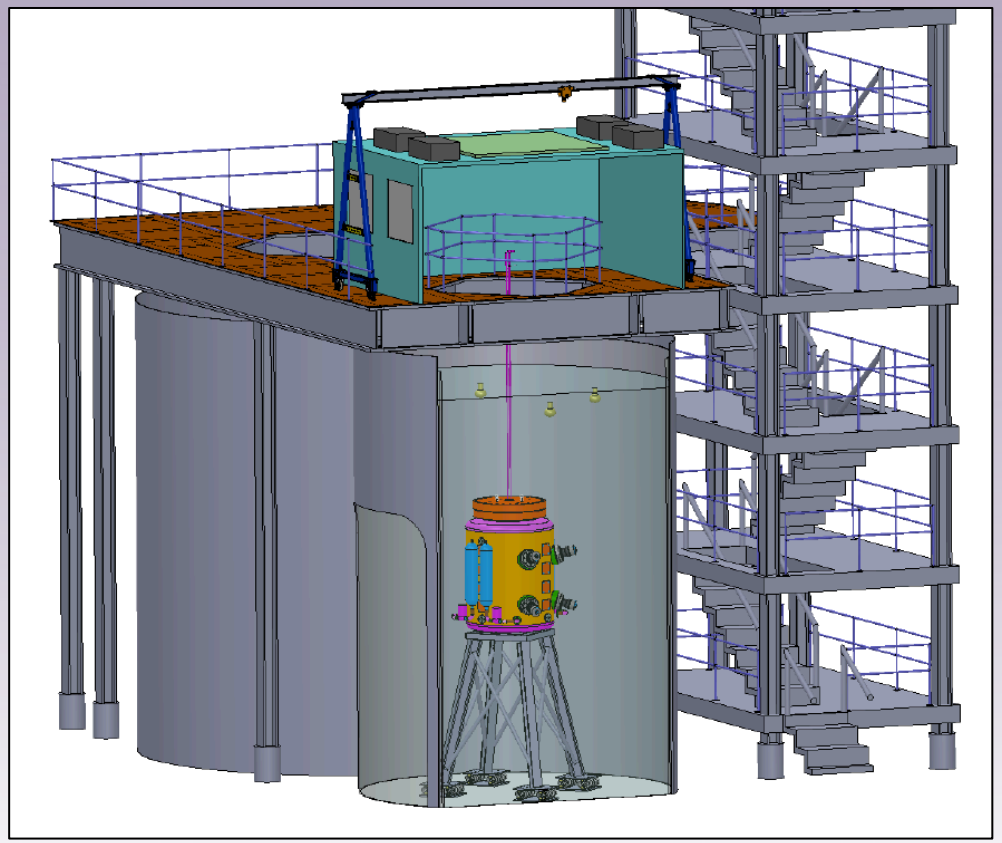
1. Added stability could allow us to push down in threshold (WIMP mass) until we hit ER backgrounds
2. Ability to use new target fluids optimized for different WIMP masses
3. Reduced neutron backgrounds, allowing us to push down in cross-section



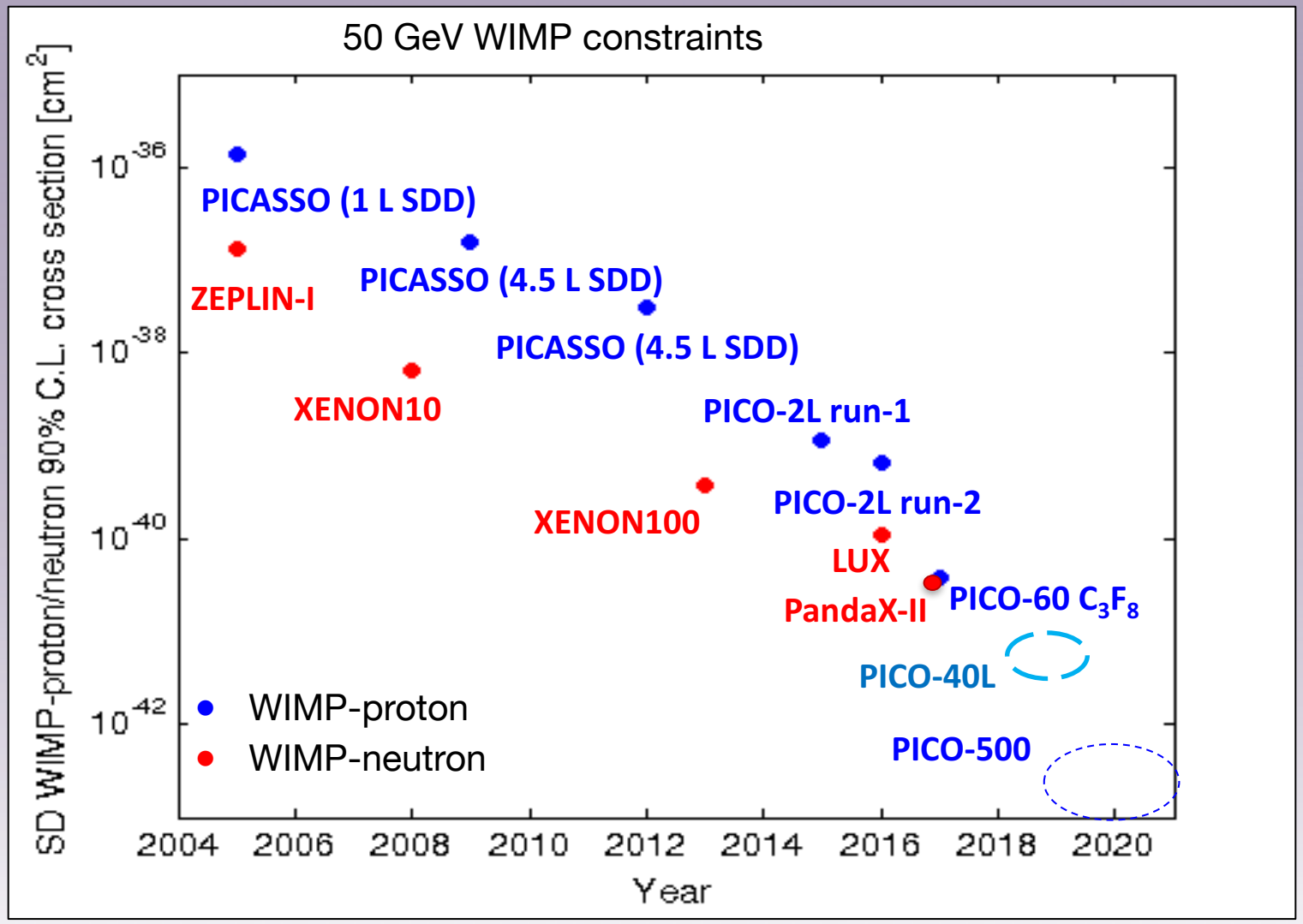
PICO-500

- Engineering work ongoing as part of R&D program
- Proposal for full detector ($3M CAD) currently submitted to CFI, decision expected this summer



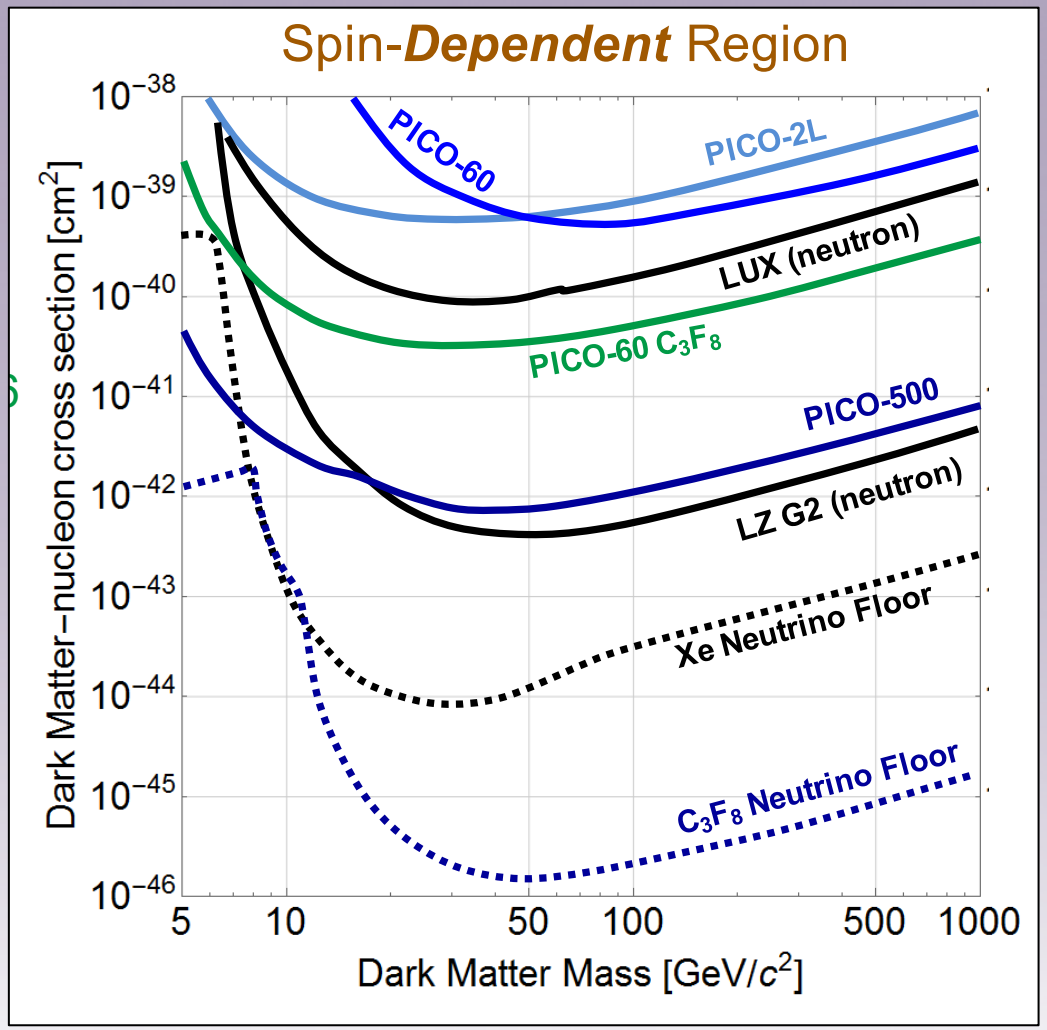


PICO Program



plot courtesy of Guillaume Giroux

Spin-Dependent Future



- PICO program has significant reach in parallel to G2 experiments
- Lower neutrino floor opens unique phase to PICO

Conclusions

- PICO bubble chambers at the 40L scale are background-free
- PICO dominates the search for spin-dependent WIMP-proton coupling
- PICO-40L will have significant physics reach by 2018
- PICO-500 will continue to probe unique phase space
- Still untapped potential in the bubble chamber technology
  - Scintillating bubble chambers: *D. Baxter et al., arXiv:1702.08861*

- **<u>The future of PICO is very bright</u>**

Acknowledgements

- Support:
  - US Department of Energy Office of Science Graduate Student Research (SCGSR) Award
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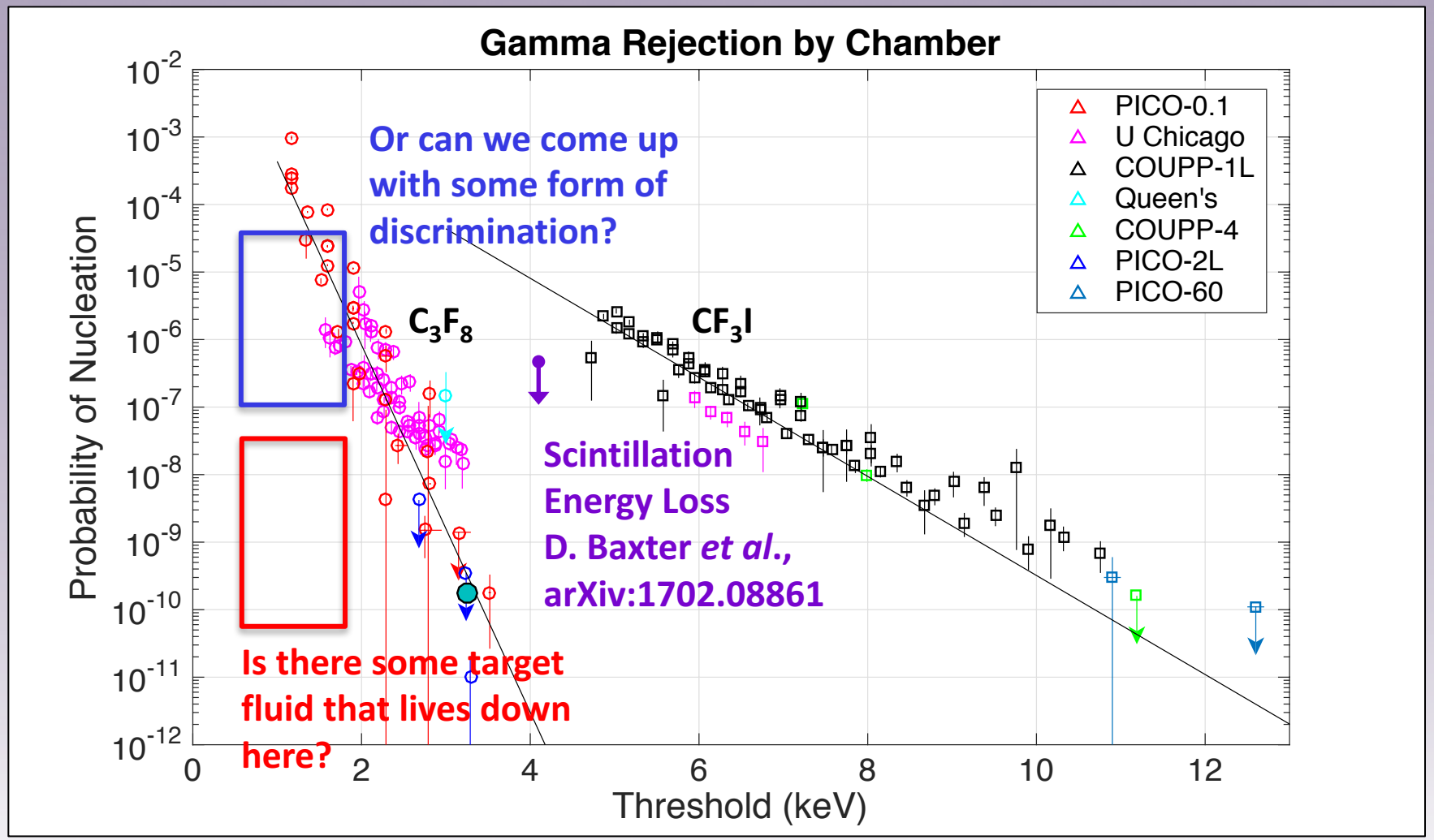
- Papers:
  - **C. Amole *et al*. (PICO Collaboration), *Dark Matter Search Results from the PICO-60 C_3F_8 Bubble Chamber*. [arXiv:1702.07666]**
  - D. Baxter *et al*. *First Demonstration of a Scintillating Xenon Bubble Chamber for Dark Matter and CEvNS Detection*. [arXiv:1702.08861]
  - C. Amole *et al*. (PICO Collaboration), *Dark Matter Search Results from the PICO-60 CF_3I Bubble Chamber*, Phys. Rev. D **93**, 052014, Published: 28 March 2016, [arXiv:1510.07754].
  - C. Amole *et al*. (PICO Collaboration), Improved Dark Matter Search Results from PICO-2L Run-2, Phys. Rev. D **93**, 061101(R), Published: 21 March 2016, [arXiv:1601.03729].
  - C. Amole *et al*. (PICO Collaboration), Dark Matter Search Results from the PICO-2L C_3F_8 Bubble Chamber, Phys. Rev. Lett. **114**, 231302, Published: 11 June 2015 [arXiv:1503.00008].

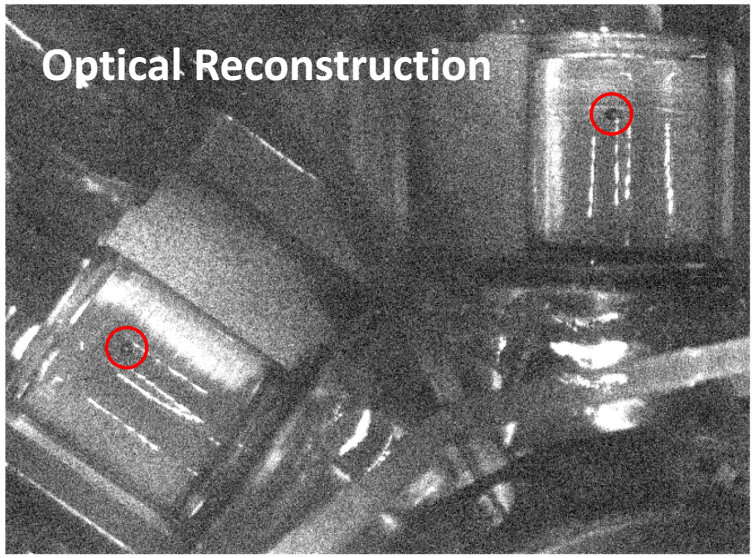

Thank you!
BAXTER

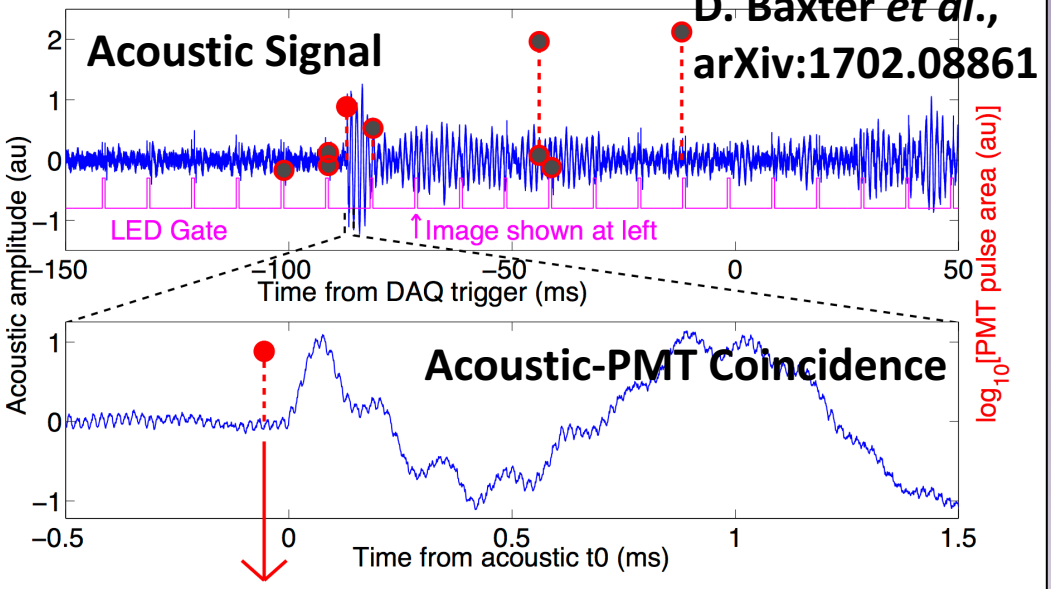
Extra Slides

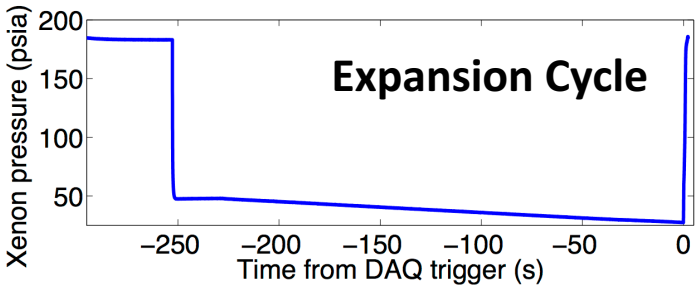
Lower Thresholds



Scintillating Bubble Chambers

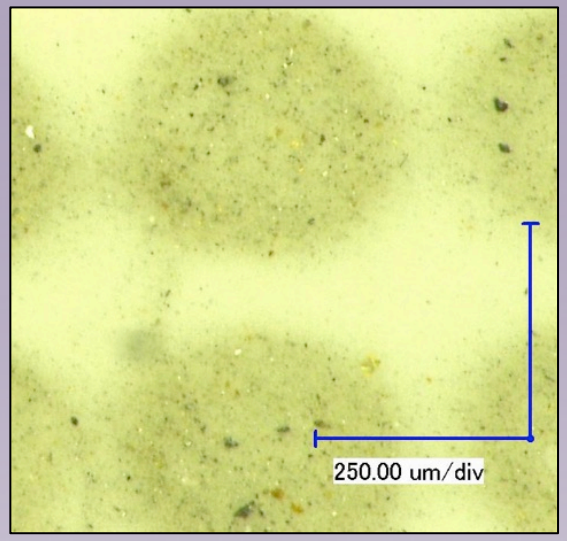




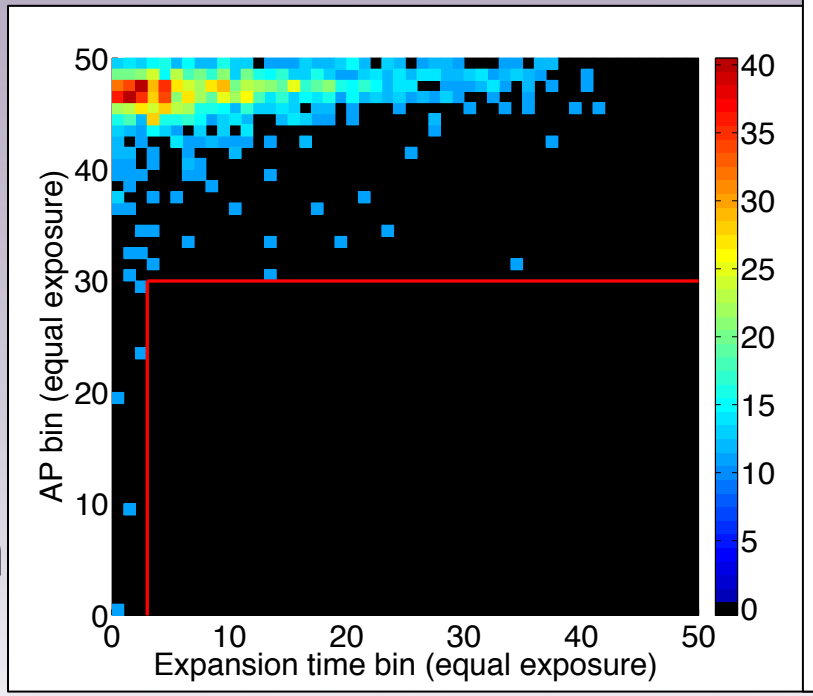


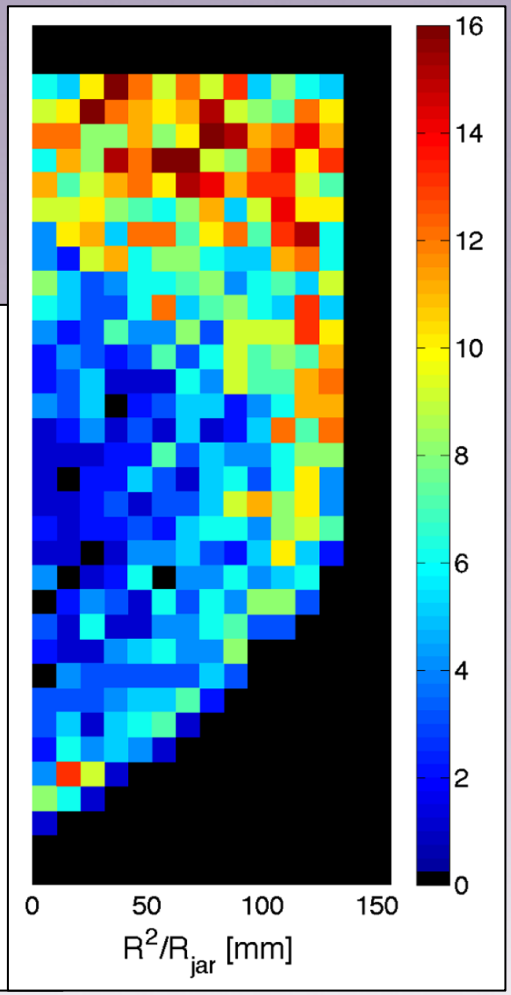
Energy Resolution!

Particulate Hypothesis



Clues from timing and spatial profiles

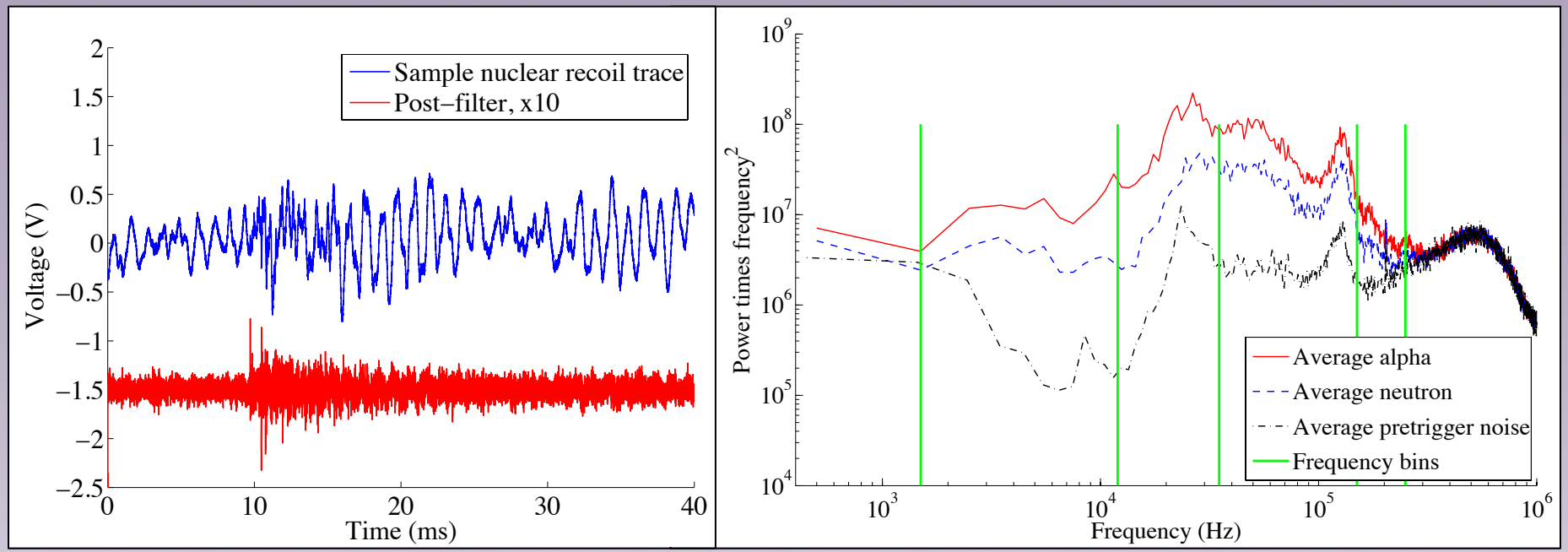




Assay reveals significant contamination

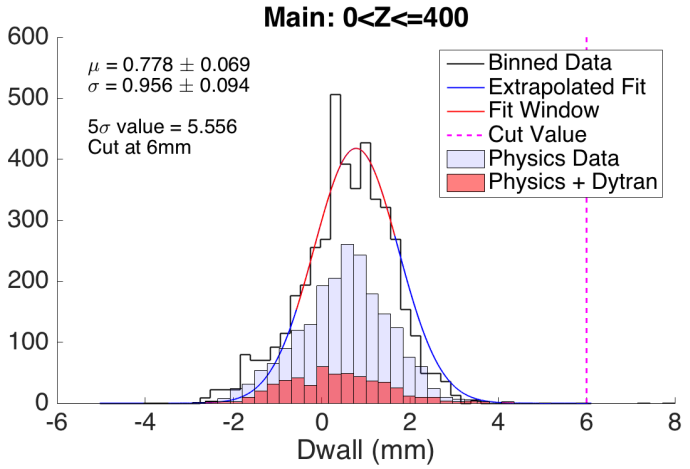
C. Amole *et al*. Phys. Rev. D 93, 052014 (2016) [arXiv:1510.07754]

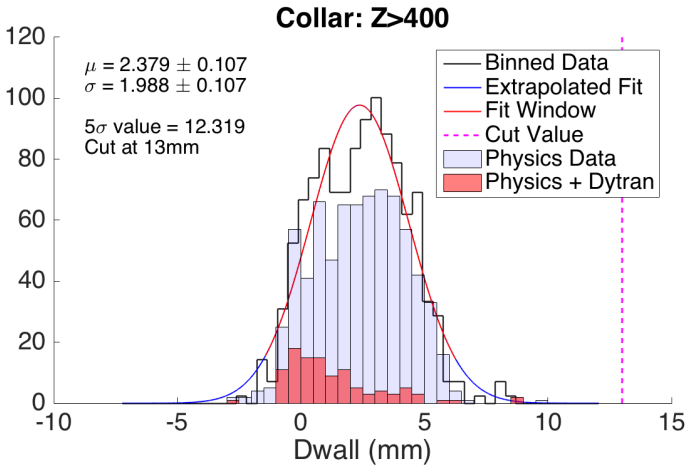
Acoustic Parameter (AP)

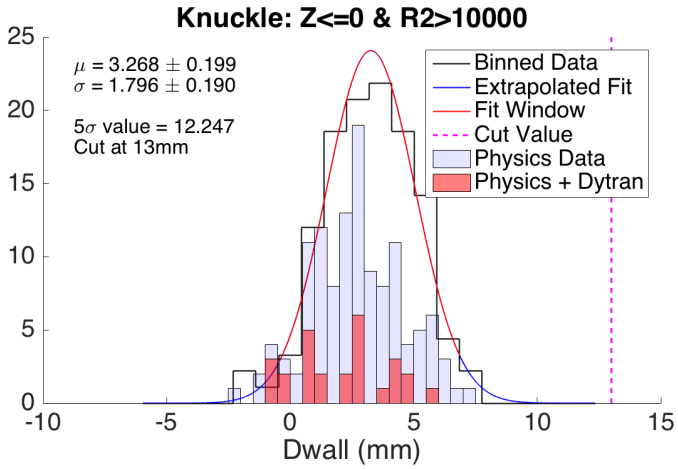


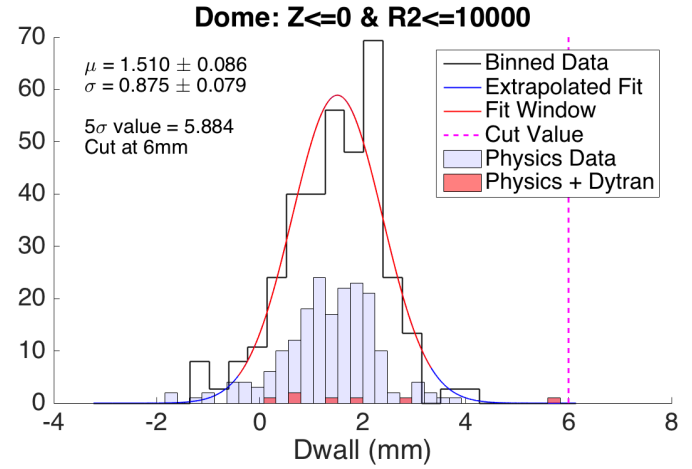
- Filter the raw trace and divide it up into frequency bands
- Correct each band for position (normalize to emitted power)
- Combine the bands that show separation between alpha and neutron data

Fiducialization

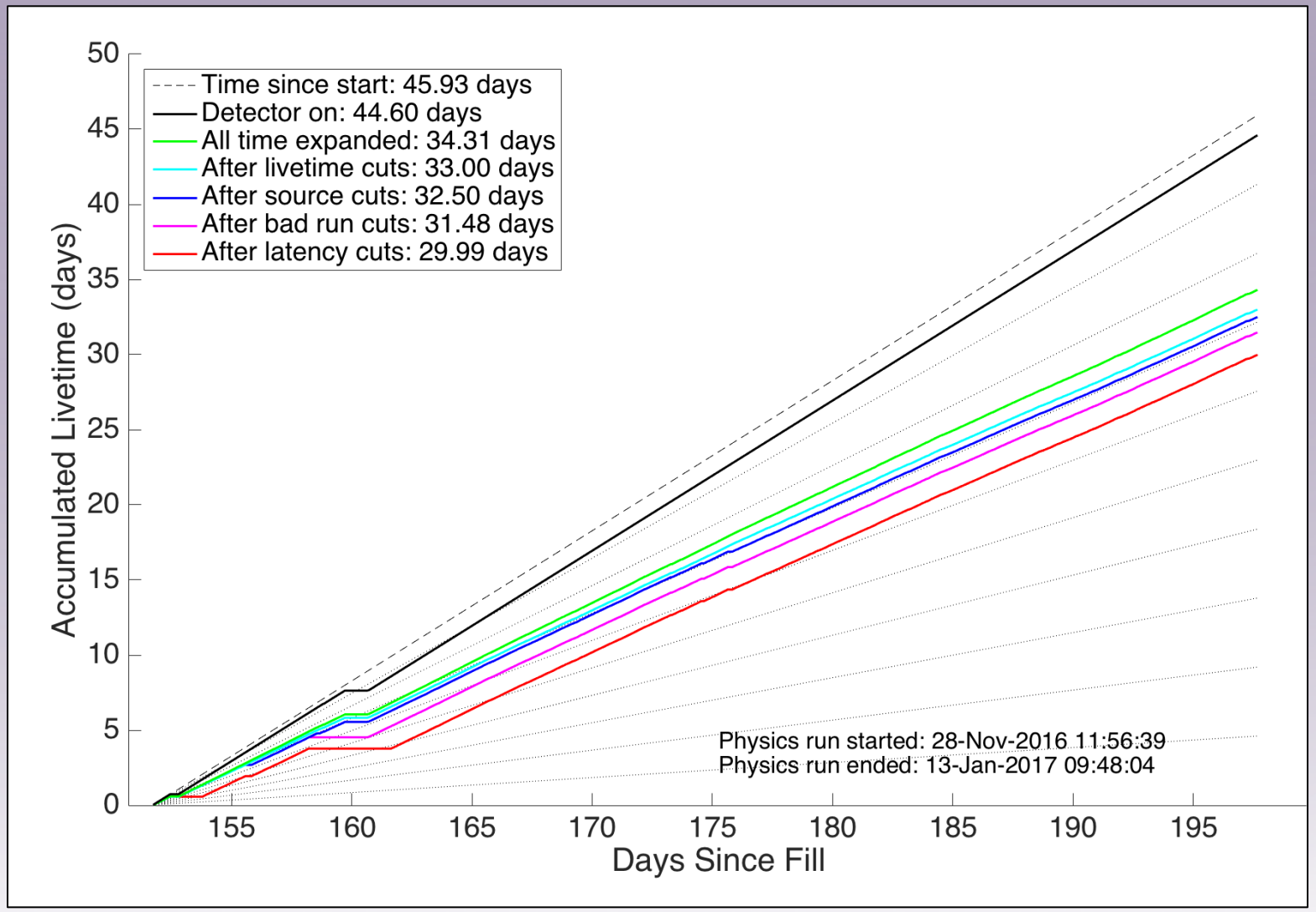








Livetime Selection



Event Selection

Acoustic information (cuts in red) were blinded for WIMP search

Cut	Description
Data Write	No errors writing to disk
Camera Trigger	Event was triggered by cameras
Pressure	Within 1psi of target
Single Bubble	Optical reconstruction algorithms found one bubble
Acoustic Noise	Pre-trigger noise was within specified range
Acoustic Timing	Acoustic signal within window of camera trigger
Fiducial	Optical reconstruction places bubble in bulk
Secondary Fiducial	Pressure rise consistent with bulk event
Acoustic Parameter (AP)	Consistent with neutron calibration
NN Score	Neural net thinks acoustics are from a neutron
Manual Scan	All events passing the above are checked